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WIND-TUNNEL TESTS OF DUAL-ROTATING PROPELLERS WITH SYSTEMATIC DIFFERENCES IN NUMBER OF BLADES BLADE SETTING, AND ROTATIONAL SPEED OF FRONT AND REAR PROPELLERS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

WIND-TUNNEL TESTS OF DUAL-ROTATING PROPELLERS WITH SYSTEMATIC DIFFERENCES IN NUMBER OF BLADES BLADE SETTING, AND ROTATIONAL SPEED OF FRONT AND REAR PROPELLERS

By W. H. Gray

SUMMARY

The advent of dual-rotating propellers has created a need for information concerning the effect of the number of blades of the front and rear propellers, relative rotational speeds, and small changes in the blade angles of the rear propeller. Results of aerodynamic tests of seven-blade propellers, which were considered as a possible arrangement to avoid vibration difficulties, are presented herein. Variations of relative blade angle and rotational speeds of the front and rear components of a six-blade dual-rotating propeller were also investigated. The test program was an extension of previous work on dual-rotating propellers at the NACA propeller-research tunnel; the propeller blades and test body were those used in the previous tests.

The results indicated that envelope efficiencies of a seven-blade propeller with three blades in the front hub and four in the rear were from 0 to $1\frac{1}{2}$ percent lower than envelope efficiencies for the six-blade dual-rotating propeller; four blades in the front hub and three in the rear resulted in efficiencies 1/2 to $3\frac{1}{2}$ percent lower than those obtained with the six-blade propeller. This conclusion applies to blade-angle settings of the front and rear propellers to absorb equal power at peak efficiency when the rotational speeds were held equal.

[redacted]

Changes in rotational speed of the rear component of a six-blade dual-rotating propeller to maintain the torque equal to that of the front component over the entire range of advance-diameter ratio rather than only at peak efficiency resulted in no appreciable effect on efficiency for either the low- or high-speed condition. The same conclusion was made for operation at constant speed ratios differing from unity by as much as ±15 percent. The rear blade angles were adjusted to provide equal front and rear propeller torque for each ratio at peak efficiency.

When the rear blade angles of the six-blade propeller were adjusted to provide equal torque at values of advance-diameter ratio other than that for peak efficiency and when rotational speeds of front and rear blades were equal, the effect on efficiency was negligible except at peak efficiency, at which a higher rear blade angle resulted in a higher efficiency.

INTRODUCTION

The use of dual-rotating propellers introduces complications into the problem of propeller-performance estimation. Propeller diameter and the number of blades are the most important parameters in the selection of a dual-rotating propeller to meet specific operating conditions. After the number of blades has been decided, there still remain the differential blade angle and the differential rotational speeds, which may be varied over the operating range. Experiments have shown that improvement in the vibration characteristics of dual-rotating propellers would also be desirable (reference 1). At present, dual-rotating propellers consist of two components having equal diameters and number of blades and operating at equal rotational speeds. The use of two components having different numbers of blades and unequal rotational speeds might materially reduce the vibration. Aerodynamic effects of such a deviation from standard practice remain to be established. The results of tests of systematic variations in blade number, differential blade setting, and differential rotational speed are presented herein. The effect of unequal number of blades has been investigated by tests of seven-blade dual-rotating propellers with three blades in the front and four in the rear and with four blades in the front and three in the rear.

The operating modes contemplated for dual-rotating propellers are those in which, throughout the operating range, the speed of the rear propeller was continuously adjusted to keep the torque of the two propellers equal, the speed of the rear propeller was held at a fixed ratio to that of the front propeller, and the blade angle of the rear propeller differed from that of the front propeller by a fixed amount. These conditions have been covered in this investigation for a six-blade dual-rotating propeller. These modes of operation cover the most important variables relating the front and rear parts of dual-rotating propellers: number of blades, blade angle, and rotational speed.

APPARATUS AND METHODS

The test setup was that used in previous tests of dual-rotating propellers in the NACA propeller-research tunnel (reference 2). A photograph of the setup with a single-rotating propeller is given in figure 1 and outline dimensions are given in figure 2. The symmetrical-airfoil wing, shown in the photograph and the drawing, was in place for all the tests.

The propeller blades, for which blade-form curves and the plan form are given in figure 3, were Hamilton Standard 3155-6 for the right-hand blades and Hamilton Standard 3156-6 for the left-hand blades. Both six- and seven-blade propellers were mounted in two hubs spaced 15 inches. The shape of the front spinner was identical with the one previously used (reference 2), but the rear spinner was elongated 5 inches because the front hub was moved forward to increase the spacing from 10 to 15 inches. This change required a slightly altered spinner and forward body section to give a faired body.

A plot of the difference in blade-angle settings for dual-rotating propellers of four to eight blades for the condition of equal torque of front and rear propellers at peak efficiency is given in figure 4.

settings for the four-, six-, and eight-blade dual-rotating propellers were those used in tests reported in references 2 and 3.

The rotational speed of the front and rear propellers was maintained equal for both the seven-blade and six-blade propellers for the investigation of the effect of changes in rear blade angles only. The speed-ratio and equal-torque tests, however, required a variation of the front and rear propeller rotational speeds that gave differences up to 30 percent.

The limiting conditions of tunnel speed (110 mph) and propeller rotational speed (550 rpm) resulted in a tip speed below 300 feet per second and a Reynolds number of about 1,000,000 for the 0.75R section, where R is the propeller radius. No effects of compressibility, therefore, would be expected.

RESULTS AND DISCUSSION

The results are presented in nondimensional form. Coefficients and symbols used are defined as follows:

C_T thrust coefficient $(T/\rho n^2 D^4)$

C_P power coefficient $(P/\rho n^3 D^5)$

η propulsive efficiency $\left(\frac{C_T}{C_P}\frac{V}{nD}\right)$

C_s speed-power coefficient $\left(\sqrt[5]{\frac{\rho V^5}{Pn^2}} \text{ or } \frac{V/nD}{\sqrt[5]{C_P}}\right)$

V/nD advance-diameter ratio

where

T effective thrust, pounds

P power absorbed by propeller, foot-pounds per second

V airspeed, feet per second

n propeller rotational speed, rps

D propeller diameter, feet

ρ mass density of air, slugs per cubic foot

β_F front blade angle at 0.75R

β_R rear blade angle at 0.75R

C_{P_F} power coefficient for front propeller

C_{P_R} power coefficient for rear propeller

The effective thrust is the measured thrust of the propeller-body combination plus the drag of the body without a propeller.

For tests in which the rotational speed of the two components differed, the following coefficients based on the rotational speed of the front propeller were used:

$$C_T = \frac{T}{\rho {n_F}^2 D^4}$$

$$C_P = \frac{P}{\rho {n_F}^3 D^5}$$

$$C_{P_F} = \frac{2\pi n_F Q_F}{\rho {n_F}^3 D^5}$$

$$C_{P_R} = \frac{2\pi n_R Q_R}{\rho {n_F}^3 D^5}$$

where

n_F front-propeller rotational speed, rps

n_R rear-propeller rotational speed, rps

Q_F front-propeller torque, foot-pounds

Q_R rear-propeller torque, foot-pounds

It will be seen that these coefficients reduce to the usual ones for the condition of equal rotational speed of front and rear components.

The figures showing propeller characteristics and efficiency comparisons are given in table I.

Seven-blade propeller.- The tests of seven-blade propellers were made with the two possible combinations of three blades in the front hub and four in the rear (designated hereinafter the three-four combination) and four blades in the front hub and three in the rear (designated the four-three combination). Rotational speeds of front and rear components were maintained equal throughout the tests. The blade angles of the front and rear propellers were set to absorb equal power at peak efficiency.

The characteristic curves for the seven-blade propellers are given in figures 5 to 14. The curves of C_T and C_P (figs. 5, 6, 10, and 11) indicate a more gradual stall for the three-four combination than for the four-three combination. This stall is more gradual probably because the larger number of blades requires a lower rear blade angle, which results in a lighter loading of the inboard sections of the rear propeller for the three-four combination.

The efficiency envelopes for the two combinations (fig. 15) are only from 0 to $3\frac{1}{2}$ percent lower than for the six-blade dual-rotating propeller in the tractor condition (from reference 2). The efficiency envelope of the three-four combination varied from no higher at a front blade angle of 20° to $1\frac{1}{2}$ percent higher at 60° than the envelope for the four-three combination (fig. 15). A comparison of efficiencies on a basis of constant C_P (fig. 16) indicated little or no consistent relationship between the efficiency curves except for the condition of peak efficiency shown by the envelopes of figure 15.

Equal-torque tests.- In previous tests of six-blade dual-rotating propellers (reference 2), the rotational speeds were maintained equal throughout the test and the rear blade angles were adjusted to attain equal torque at peak efficiency. In the present investigation, tests were made to determine the effect of varying the speed of the rear component to maintain equal torque throughout the range of V/nD as well as at peak efficiency; the blade angles were the same as in the tests of reference 2. These tests may therefore be compared with the tests of reference 2 for peak efficiency. The V/nD intercepts of the thrust curves must coincide in order that the curves obtained from the present tests may be compared with results obtained from previous tests. The intercepts did coincide for blade angles of 20° and 30°. The intercepts differed slightly, however, for the blade angles of 40°, 50°, and 60° and new thrust- and power-coefficient curves (figs. 17 and 18) were obtained from interpolation by assuming that the slight shift was equivalent to an effective shift in blade angle. The individual power-coefficient curves obtained from test data without interpolation are presented in figure 19.

New efficiency curves for the blade angles of 40°, 50°, and 60° were computed and plotted from the interpolated thrust- and power-coefficient curves, so that all efficiency plots on figure 20 are effectively those for the corresponding blade angles used in the previous tests. Only a slight increase in efficiency due to adjusting the propeller speed to provide equal torque is indicated in the range of climb. Because the present condition of testing is the same as the previous condition at peak efficiency, the efficiency envelopes from the two sets of tests should coincide. There is a difference of 1 to $1\frac{1}{2}$ percent between the envelopes (fig. 21); the envelope obtained from the equal-torque tests is lower. This difference is within the limit of agreement that can be expected of tests intended to reproduce conditions of much earlier tests.

Speed-ratio tests.- Adjustment of the rotational speed of one component of a dual-rotating propeller within small limits should provide adequate means for control of front- and rear-propeller operating conditions; that is, equal power absorption could be obtained for any of the various conditions of flight. Tests at constant values of the speed ratio were made with the six-blade dual-rotating propeller. The front blade angle was set at 40° and the rear blade angle was adjusted to provide equal torque at peak efficiency. The characteristics for rotational-speed ratios from 0.85 to 1.15 (figs. 22 and 23) indicated no appreciable effect on efficiency.

Figure 24 is a cross plot of the characteristics and indicates the manner in which the torque ratio changes with speed ratio. At a V/nD of 0.7, decreasing the speed of the rear propellor 30 percent decreased the rear-propeller torque and increased the torque ratio Q_F/Q_R by 9 percent.

Blade-angle tests.- The effect of a fairly large difference in rear blade angle with equal front and rear rotational speeds was investigated for a blade-angle range of 20° to 60°. Figures 25 to 34 present the characteristic curves of these tests. As would be expected, a decrease in rear blade angle, corresponding to an increasing inability to remove the rotation imparted to the slipstream by the front propeller, resulted in decreased efficiency; the higher the front blade angle, the larger the difference.

For each value of front blade angle a value of rear blade angle was selected such that equal torque would be absorbed by front and rear propellers approximately at a V/nD for peak efficiency. Other rear blade angles were then selected to give equal power absorption at values of V/nD below the value for peak efficiency and down to values that would occur in the climb condition. Within the experimental accuracy there was apparently no effect on the power absorption of the front propeller due to a shift in blade angle of the rear propeller. For each value of front blade angle, therefore, only one faired average curve of C_P for the front propeller was used (figs. 26, 28, 30, 32, and 34).

The three envelopes of figure 35 have been obtained by fairing envelopes through the peaks of efficiency curves obtained from blade-angle settings giving equal front and rear power absorption at 0.35, 0.65, and 1.00 times the value of V/nD for peak efficiency. These envelopes emphasize the necessity for readjusting the blade angles to those providing equal power absorption at V/nD for peak efficiency, when the propeller is operating in the high-speed range. Except for the high-speed condition, there was little apparent effect of blade-angle change; figure 36 (C_T at constant C_P) shows little deviation except at V/nD for peak efficiency (for example, at V/nD of approx. 3.6 for $C_P = 0.4$).

Figures 37 to 39 are cross-plotted data of thrust-power ratio against C_P for the conditions of $C_{P_F} = C_{P_R}$ at 0.35, 0.65, and 1.00 times the value of V/nD for peak efficiency. The curve for a V/nD of 2.5 appears to be somewhat in error, especially in figure 37, and should be lower. The error is experimental, however, and could not be faired out. Superposition of these plots again showed that at constant C_P and V/nD there was little or no effect of blade-angle difference on thrust-power ratio (or efficiency at constant power) until the high values of V/nD were reached.

CONCLUDING REMARKS

Tests were made of a six- and a seven-blade dual-rotating propeller of the same size and blade design. The seven-blade propeller was tested with three blades in the front hub and four in the rear (three-four combination) and with four blades in the front hub and three in the rear (four-three combination).

1. The results of tests at equal rotational speeds with the blade angles of the front and rear components of the seven-blade propeller adjusted to give equal power absorption at peak efficiency may be summarized as follows:

(a) Peak efficiencies were from 0 to $3\frac{1}{2}$ percent less than for the similar six-blade dual-rotating propeller, depending on blade-angle setting and the type of seven-blade combination.

(b) Peak efficiencies of the three-four combination were from 0 to $1\frac{1}{2}$ percent higher than those of the four-three combination, depending on the blade-angle setting.

(c) There was no appreciable difference in efficiencies of the two combinations except in the range of advance-diameter ratio near peak efficiency.

2. For the six-blade dual-rotating propeller, adjusting the speed of the rear component to maintain its torque equal to that of the front component had no significant effect on efficiency.

3. For the six-blade dual-rotating propeller at a blade angle of 40°, operating at fixed values of rotational-speed ratio from 0.85 to 1.15 had no considerable effect on efficiency when the rear blade angle was set to give a torque equal to that of the front propeller at peak efficiency.

4. For a six-blade dual-rotating propeller at equal rotational speeds of front and rear components, changes in rear blade angle did not affect the low-speed (take-off and climb) operating efficiency but reducing the rear blade angle did result in a lower high-speed efficiency. The effect was greater at the higher front blade angles.

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1. Miller, Mason F.: Wind-Tunnel Vibration Tests of Dual-Rotating Propellers. NACA ARR No. 3I11, 1943.

2. Biermann, David, and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade Single- and Dual-Rotating Tractor Propellers. NACA Rep. No. 747, 1942.

3. Biermann, David, and Gray, W. H.: Wind-Tunnel Tests of Eight-Blade Single- and Dual-Rotating Propellers in the Tractor Position. NACA ARR, Nov. 1941.

TABLE I.- PROPELLER CHARACTERISTICS AND EFFICIENCY COMPARISONS

Figure	Number of blades	β_F at 0.75R (deg)	Test condition	Types of curve
5 to 9	7	10 to 60	3 blades in front hub, 4 blades in rear hub	Propeller characteristics
10 to 14	7	20 to 60	4 blades in front hub, 3 blades in rear hub	Propeller characteristics
15 and 16	7	--------	Both combinations	Efficiency comparison
17 to 20	6	20 to 60	Equal torque	Propeller characteristics
21	6	--------	Equal torque, equal speed	Efficiency comparison
22 to 24	6	40	Speed ratio	Propeller characteristics
25 to 34	6	20 to 60	Change in rear blade angle	Propeller characteristics
35	6	--------	--do--	Efficiency comparison
36	6	--------	--do--	C_T at constant C_P
37 to 39	6	--------	--do--	Thrust-power ratio plotted against C_P

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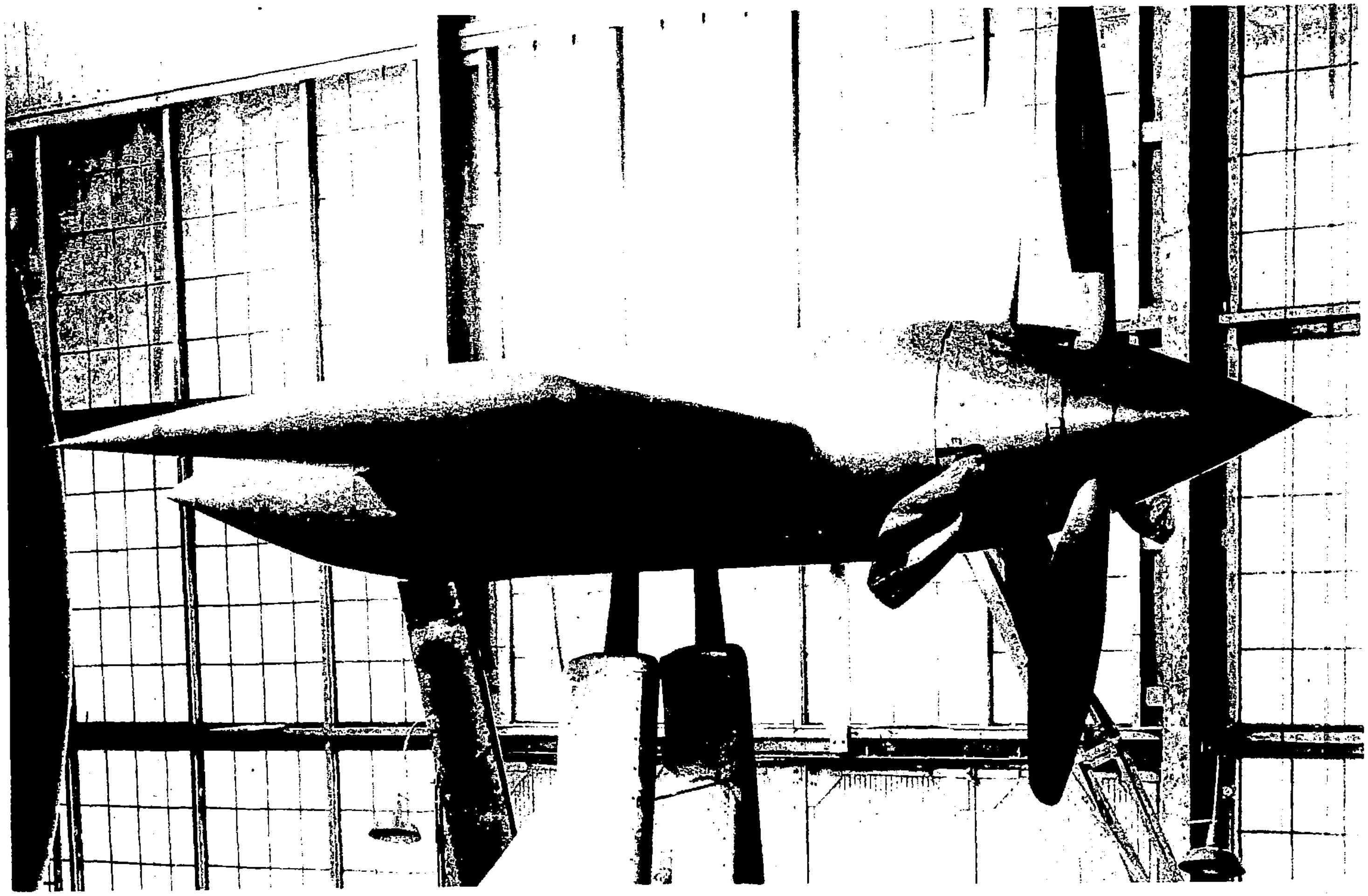

Figure 1.- Test setup. Six-blade single-rotating propeller with wing.

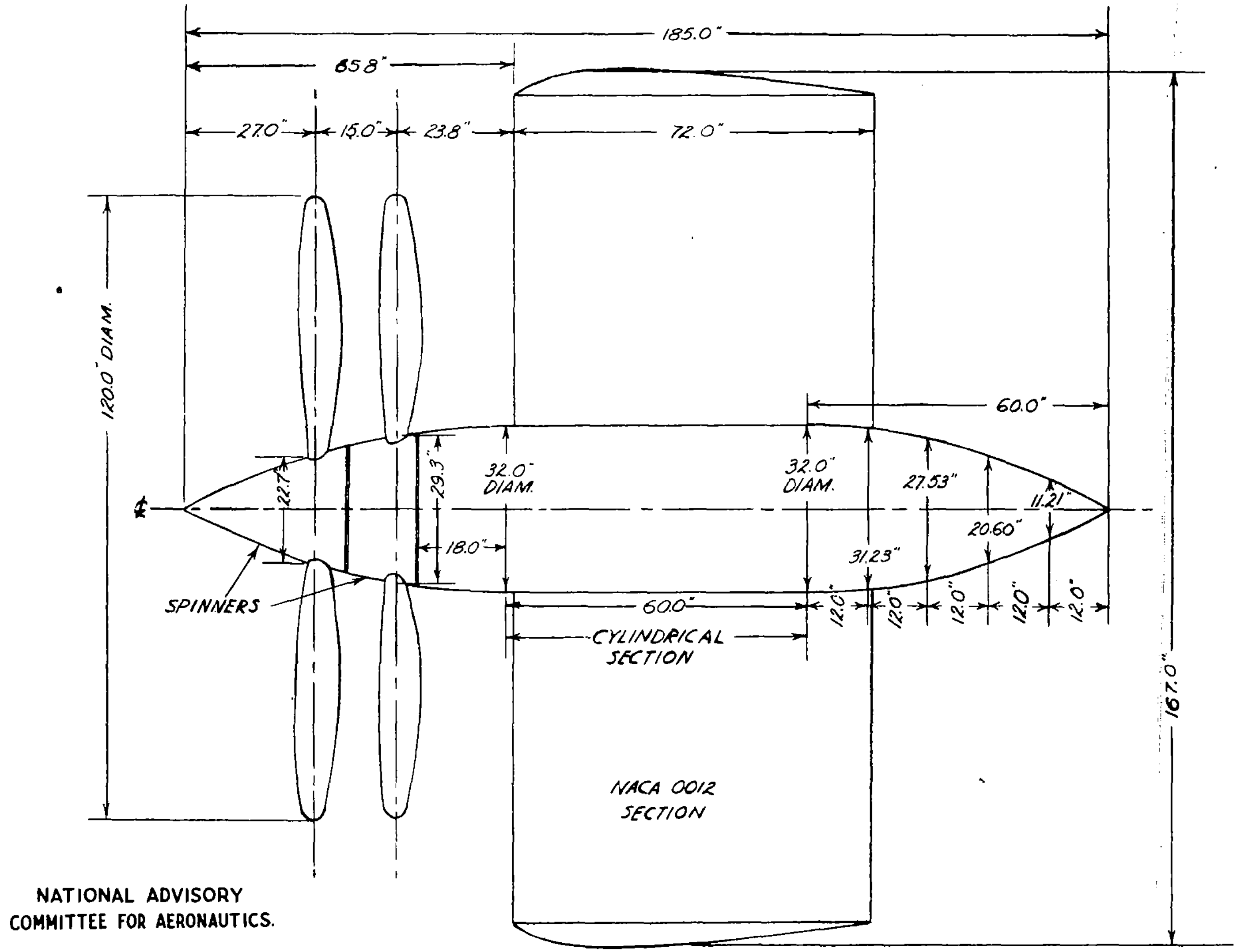

Figure 2.-Plan view showing dimensional details of wing and nacelle.

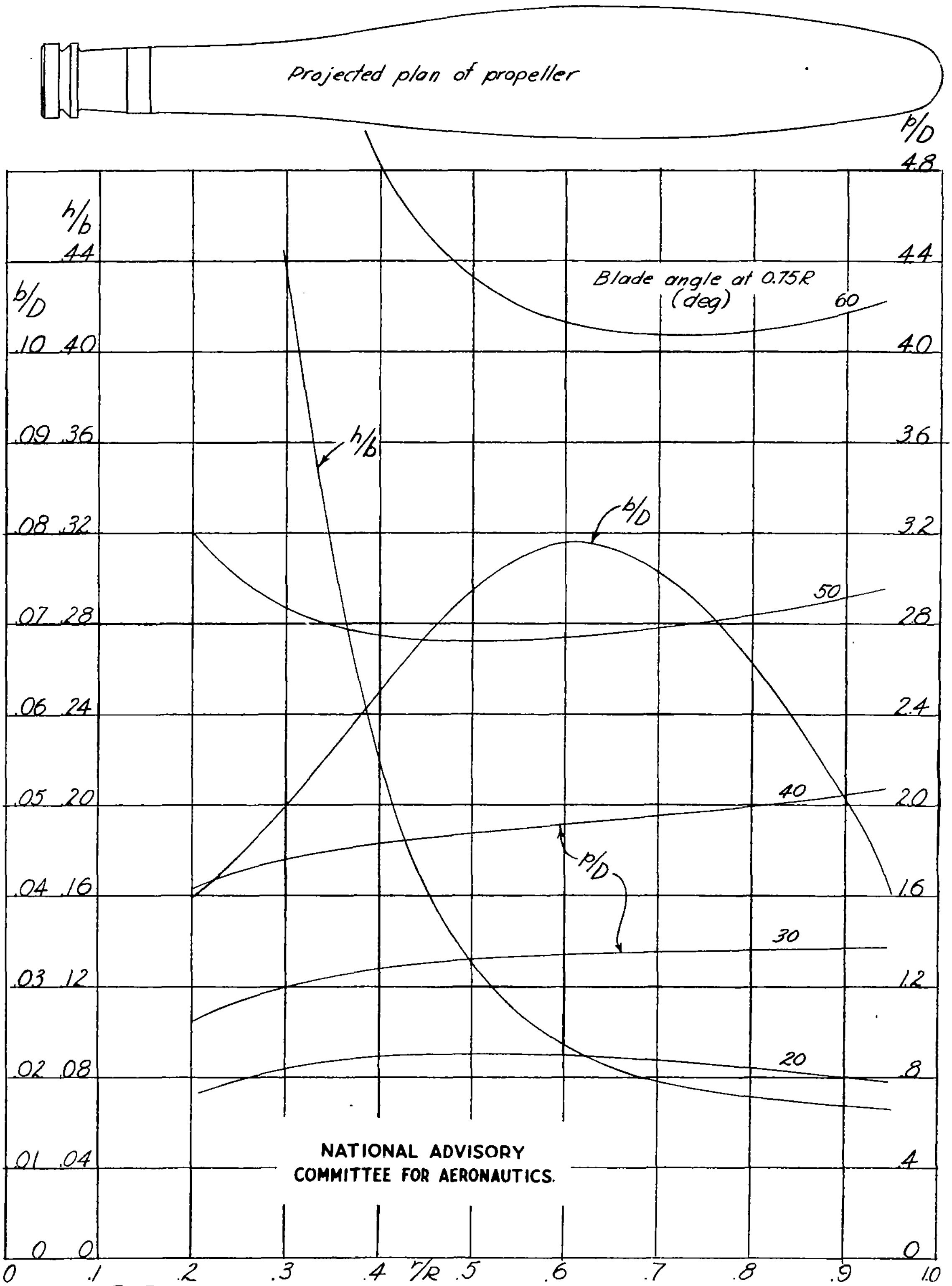

Figure 3.- Plan form and blade-form curves for propellers 3155-6 and 3156-6. D, diameter; R, radius to the tip; r, station radius; b, section chord; h, section thickness; p, geometric pitch.

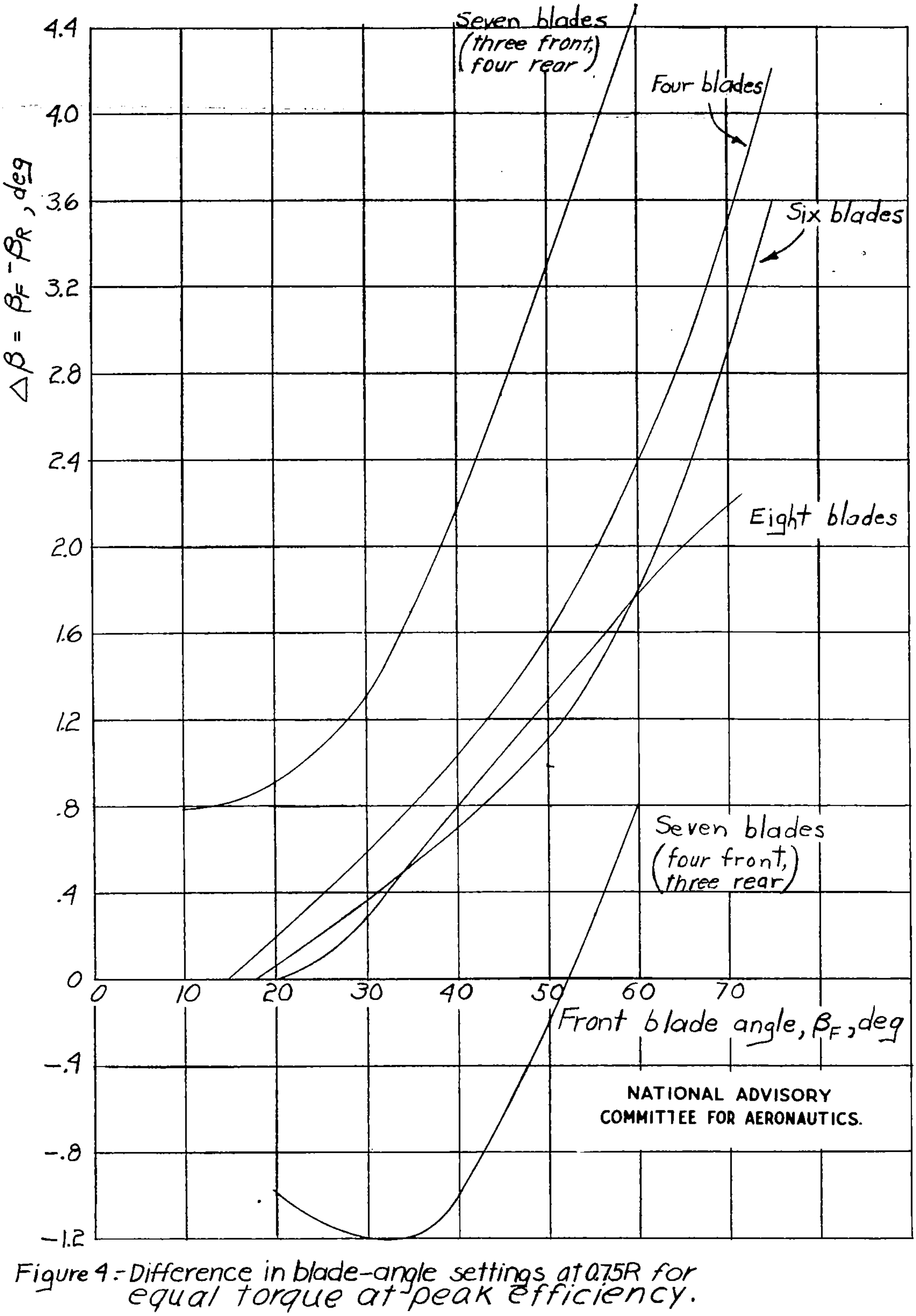

Figure 4.- Difference in blade-angle settings at 0.75R for equal torque at peak efficiency.

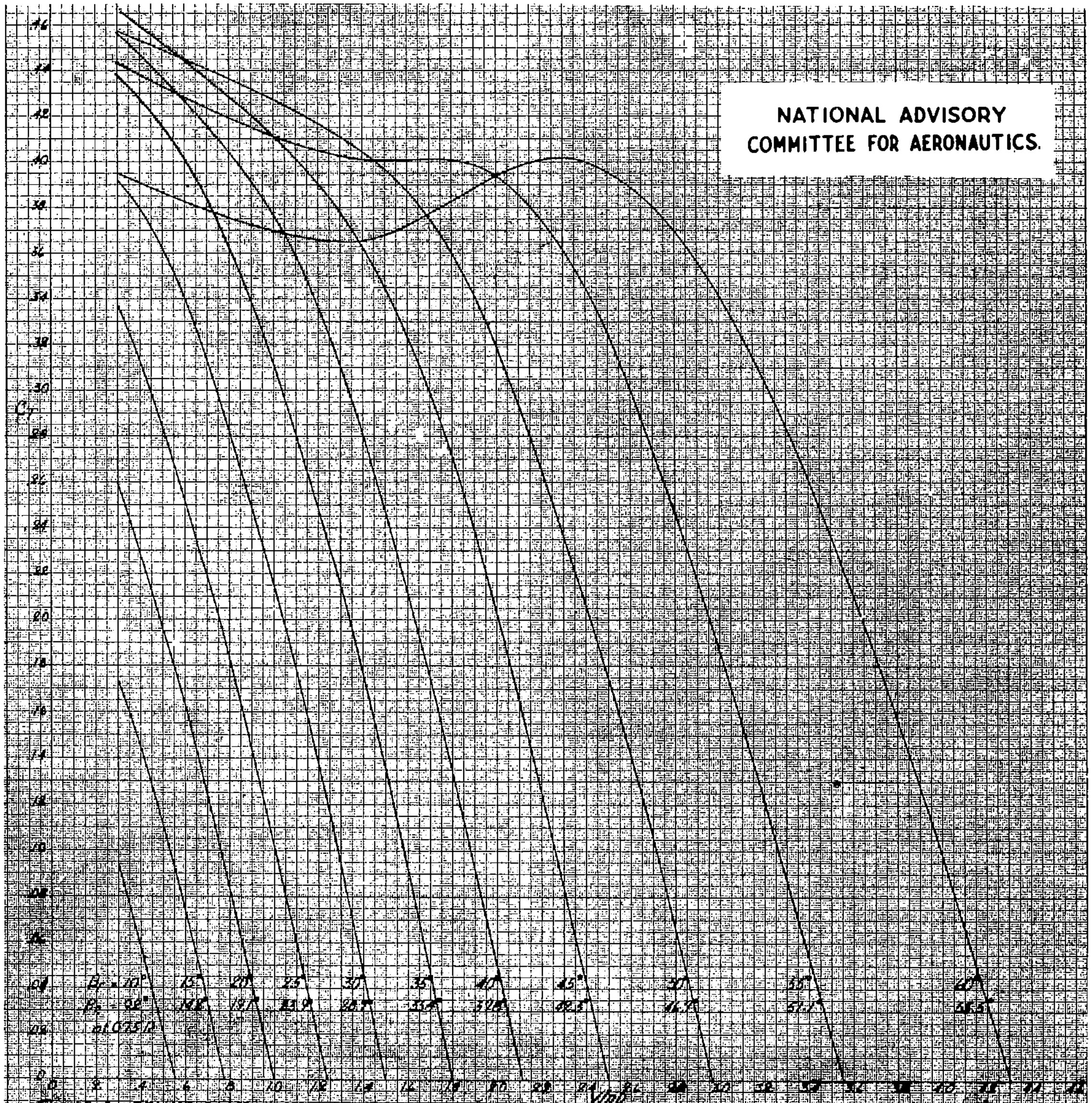

Figure 5.- Thrust-coefficient curves for seven-blade dual-rotating propeller; three-four combination.

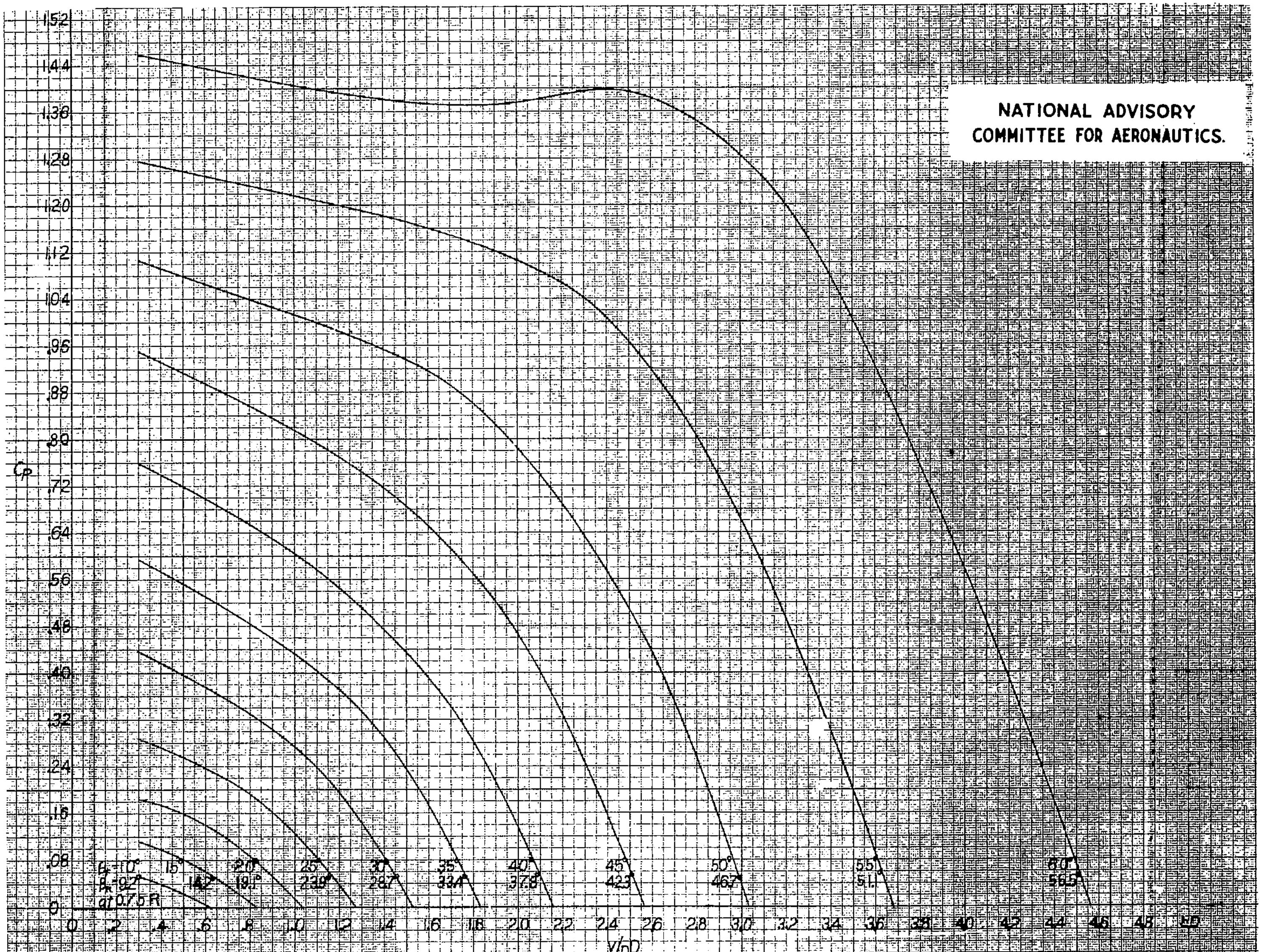

Figure 6.- Power-coefficient curves for seven-blade dual-rotating propeller; three-four combination.

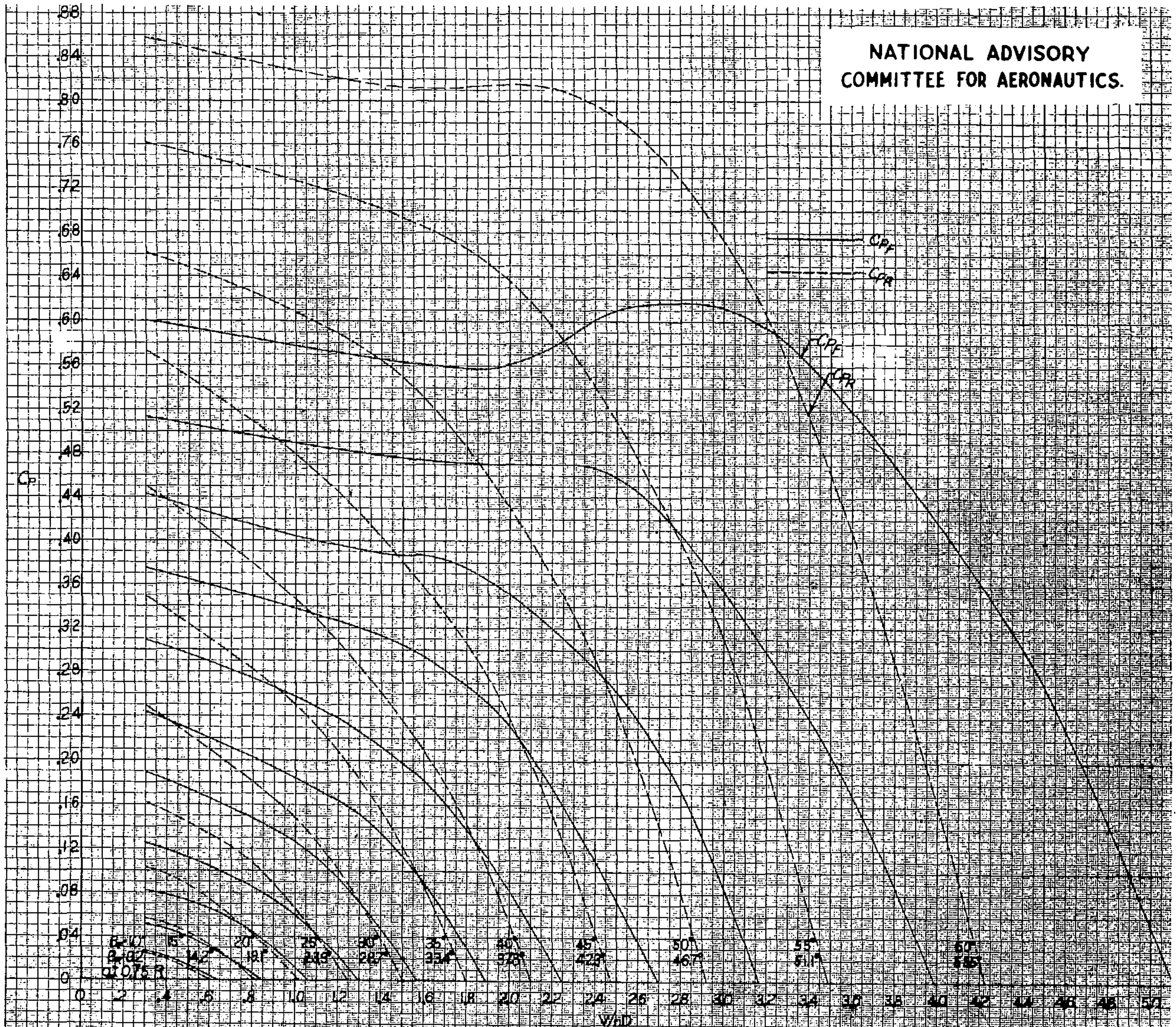

Figure 7.- Individual power-coefficient curves for seven-blade dual-rotating propeller; three-four combination.

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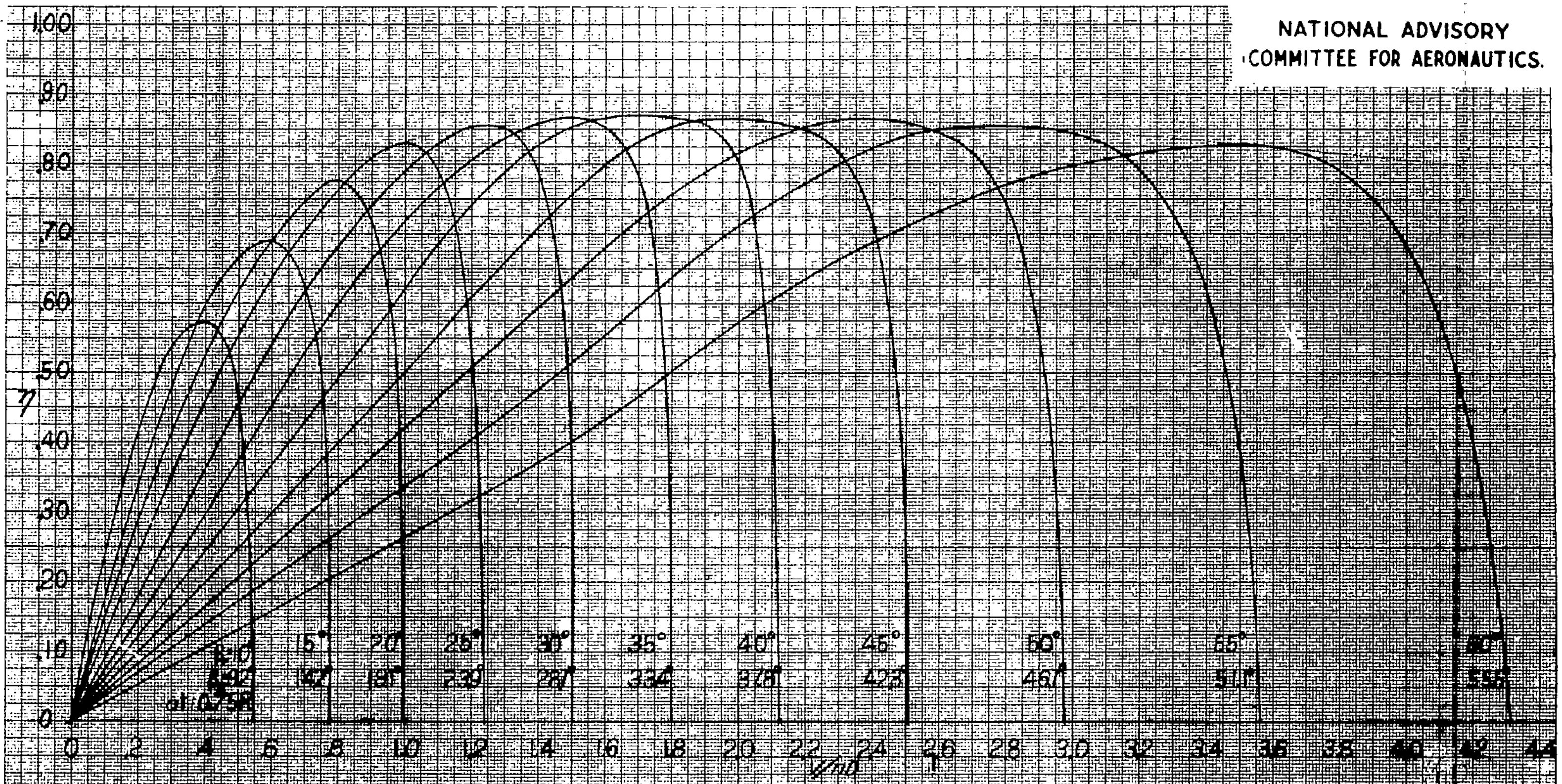

Figure 8.- Efficiency curves for seven-blade dual-rotating propeller; three-four combination.

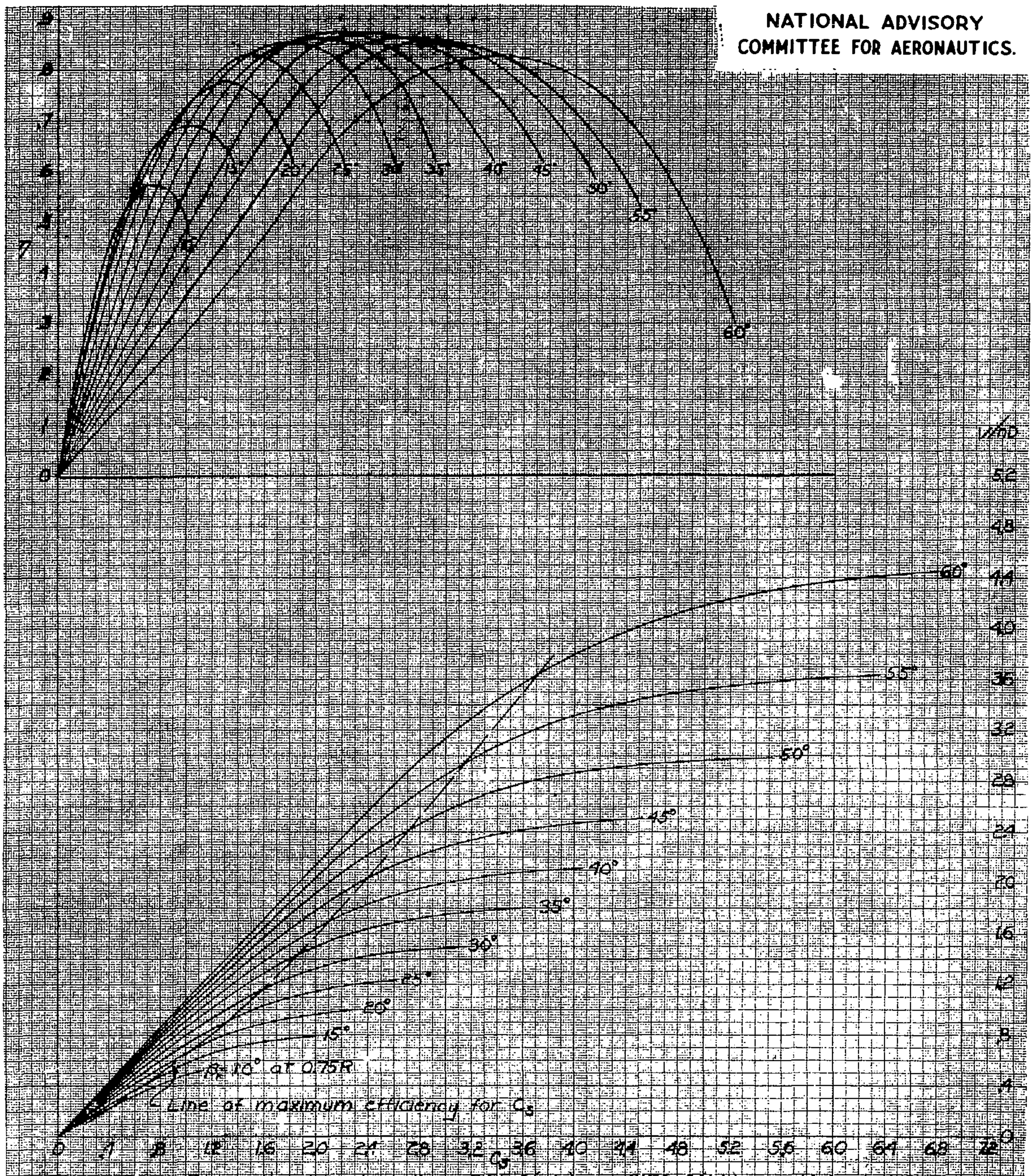

Figure 5. — Design chart for propellers 3155-6(r.h.) and 3156-6(l.h.), seven-blade dual-rotating propeller, three-four combination.

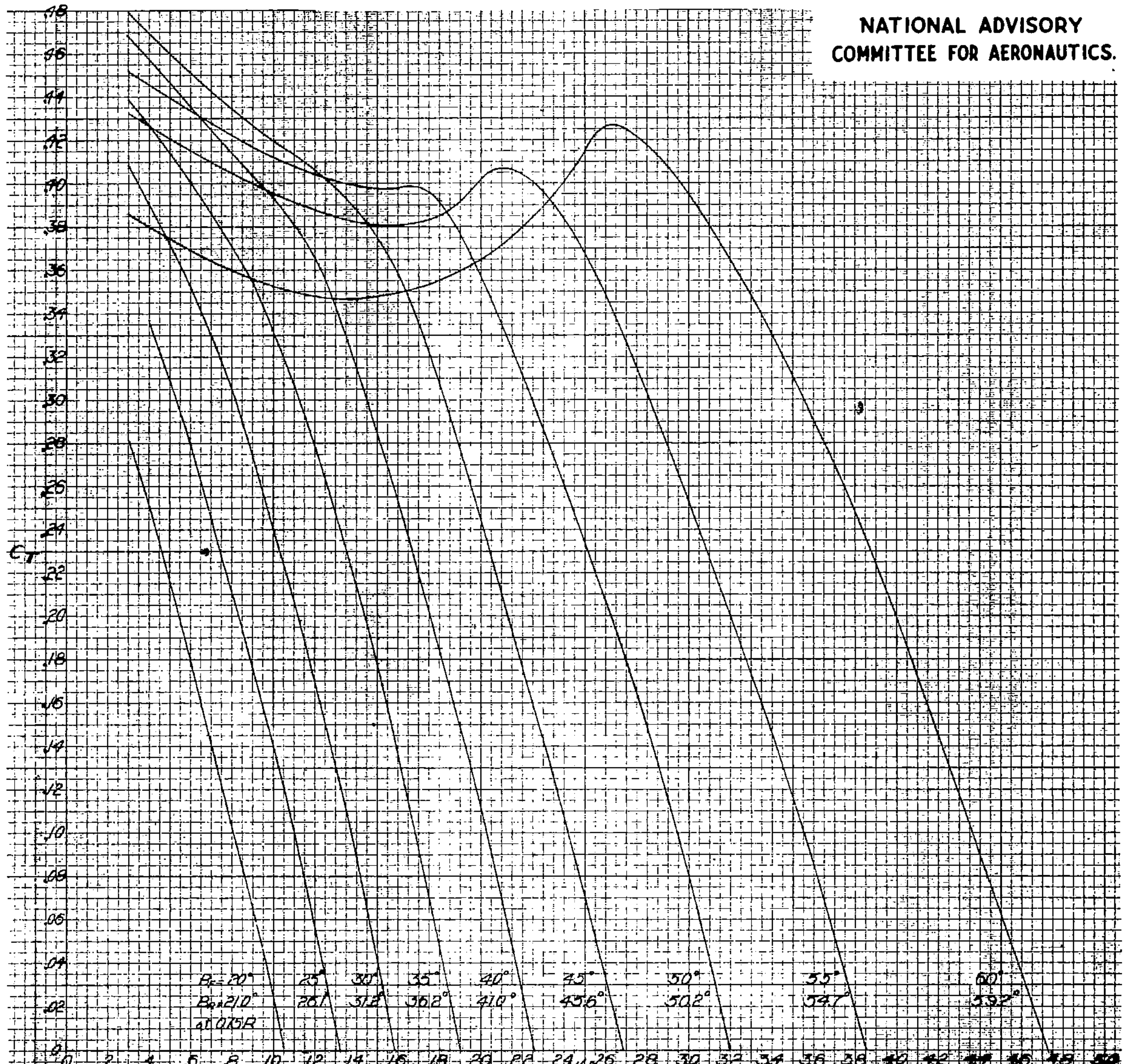

Figure 10.- Thrust-coefficient curves for seven-blade dual-rotating propeller; four-three combination.

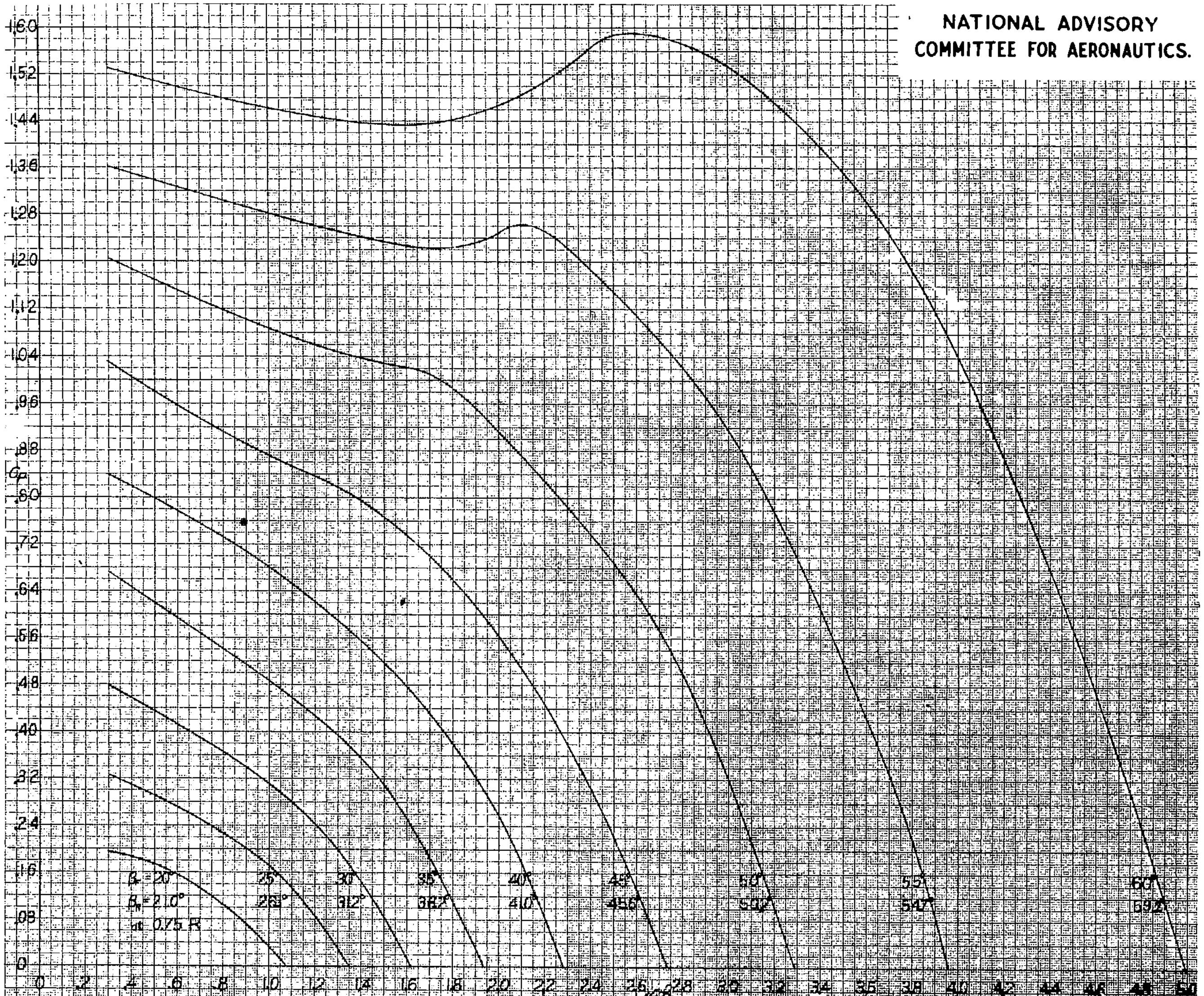

Figure 11.- Power-coefficient curves for seven-blade dual-rotating propeller; four-three combination.

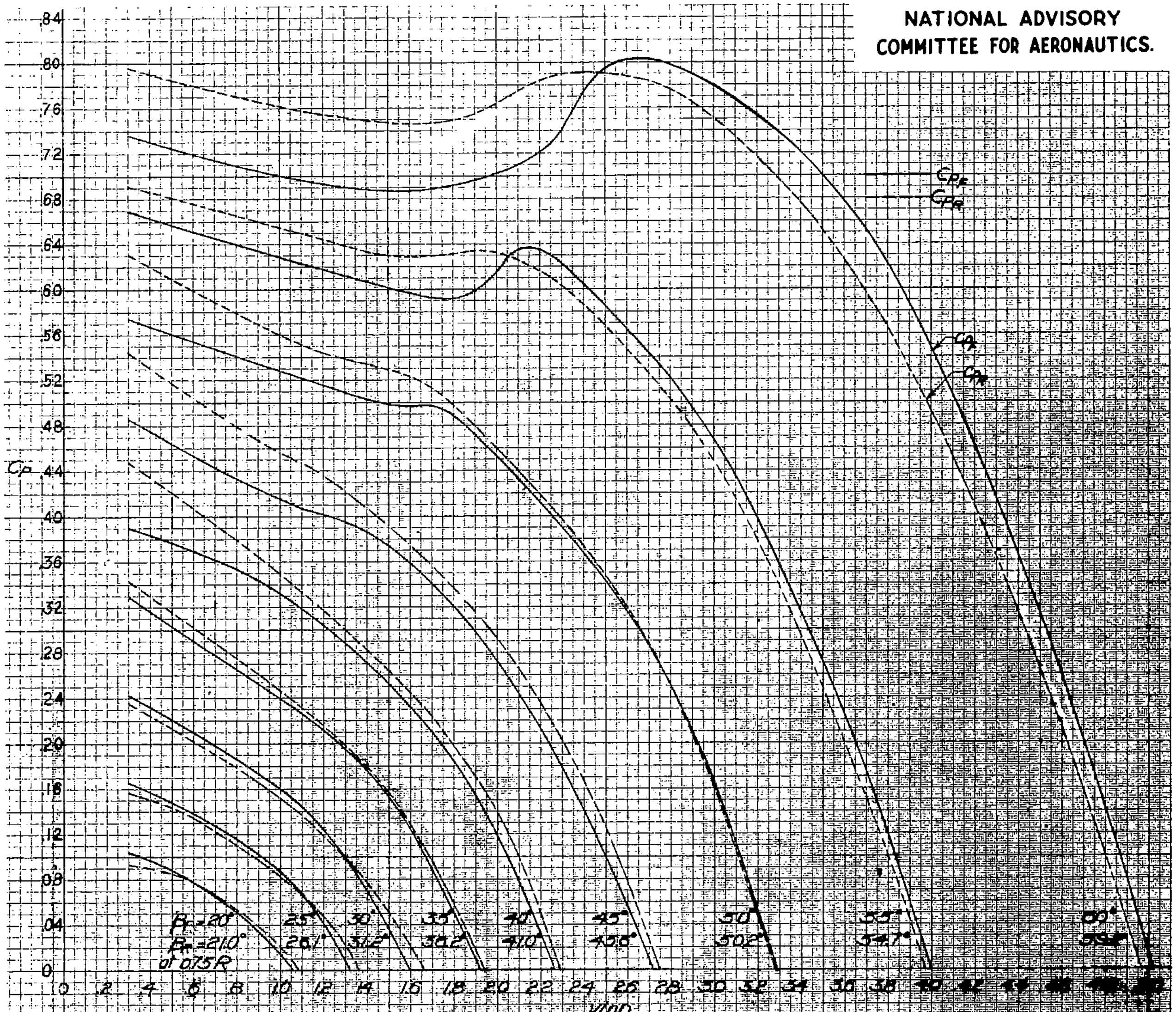

Figure 12.- Individual power-coefficient curves for seven-blade dual-rotating propeller, four-three configuration.

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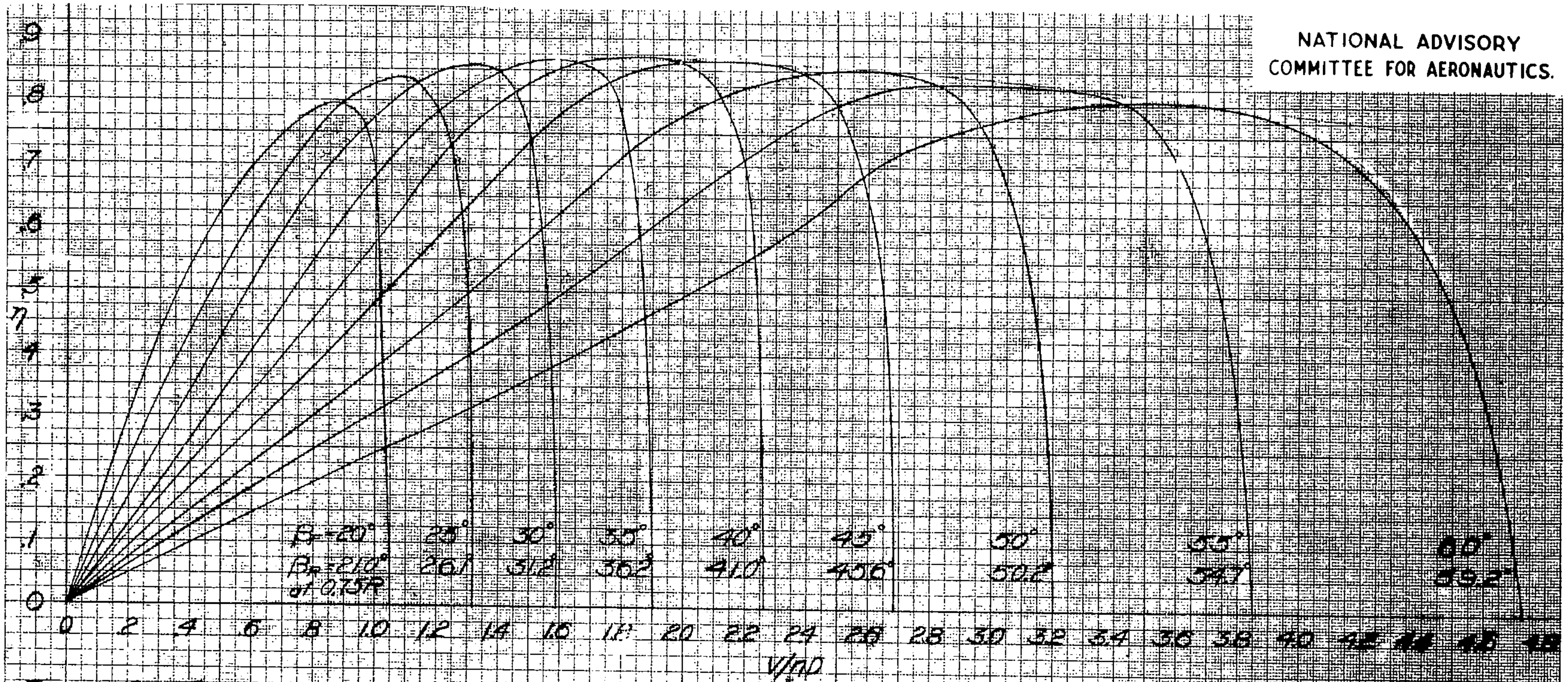

Figure 13 – Efficiency curves for seven-blade dual-rotating propeller; four-three combination.

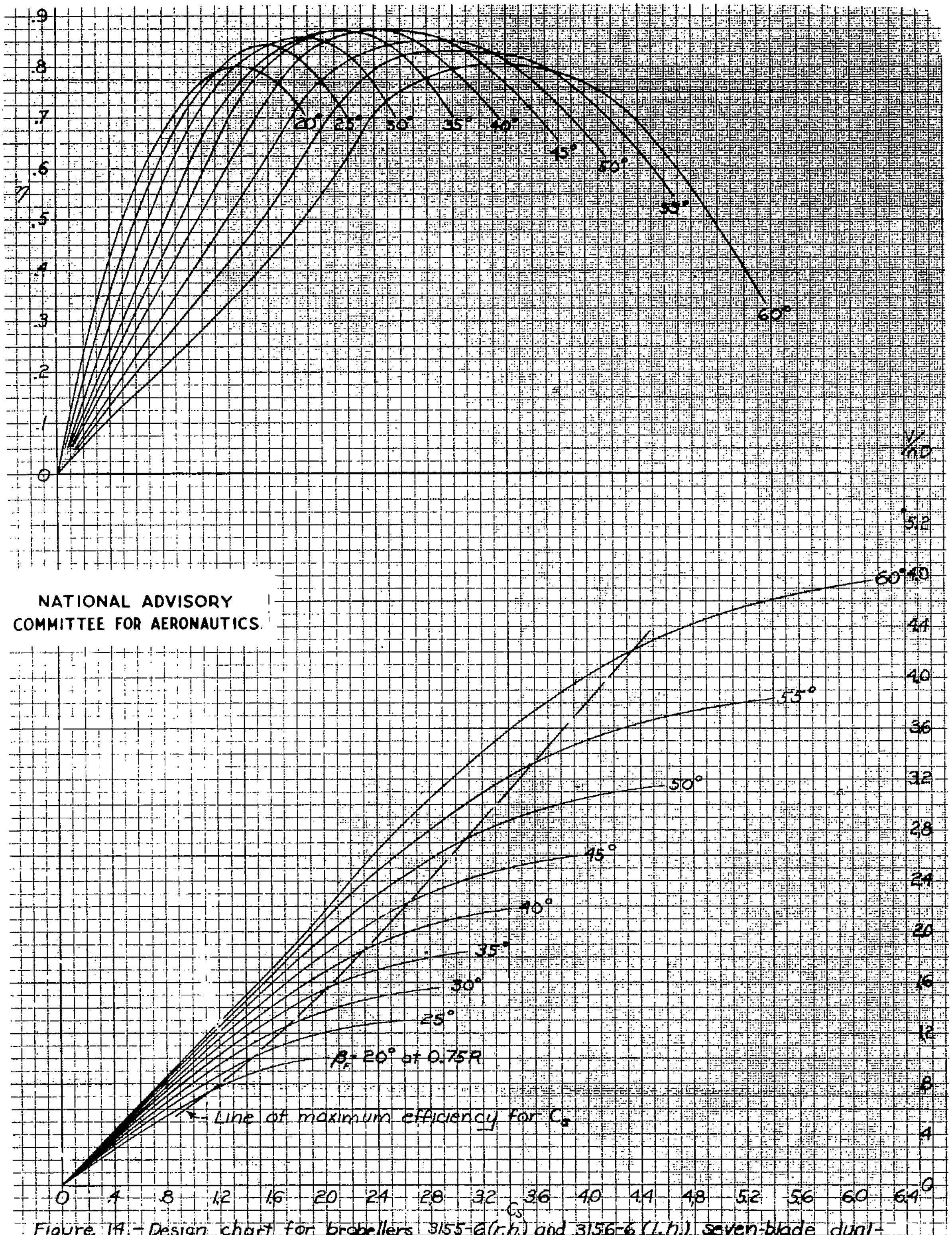

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Figure 14.- Design chart for propellers 3155-6(r.h.) and 3156-6 (l.h.), seven-blade dual-rotating propeller; four-three combination.

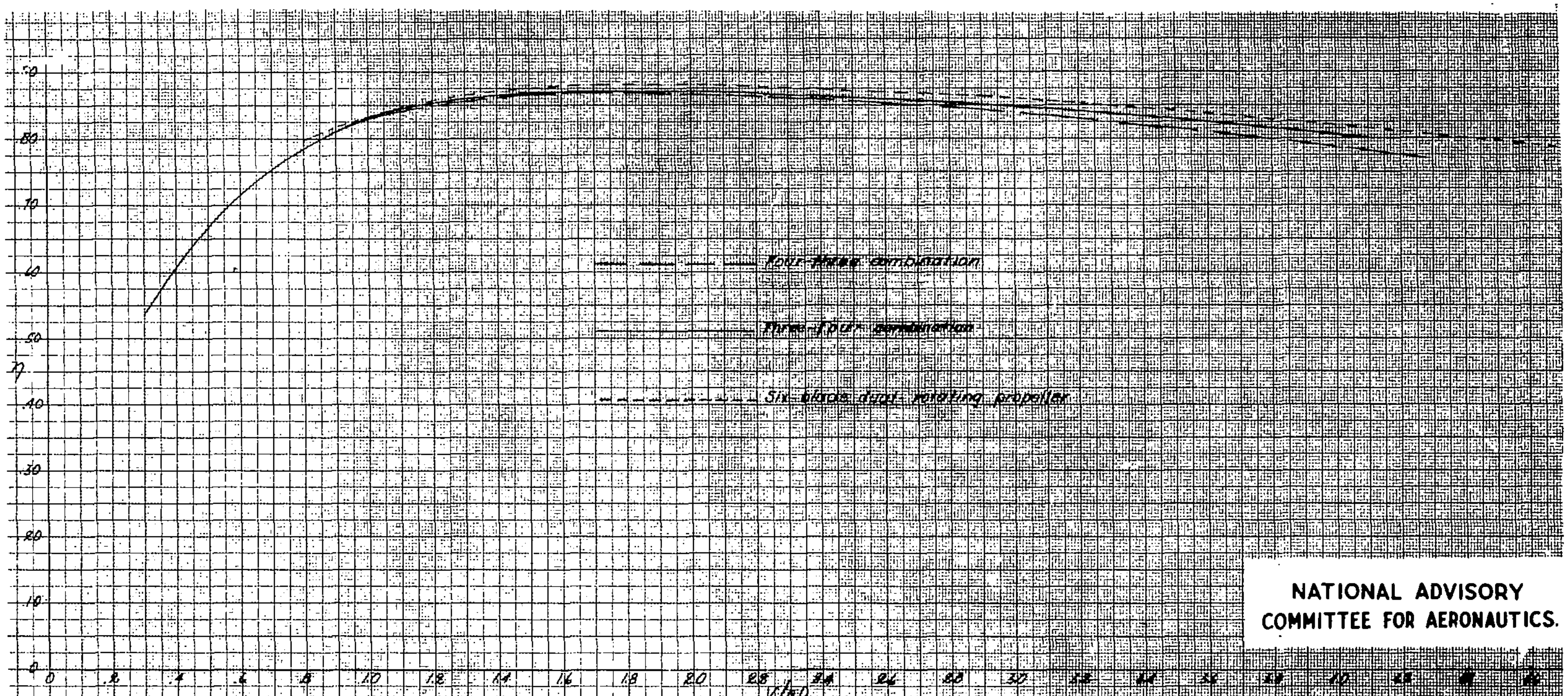

Figure 15.- Efficiency envelopes for two combinations of seven-blade dual-rotating propellers. Envelope for six-blade dual-rotating propeller (from reference 2) added for comparison.

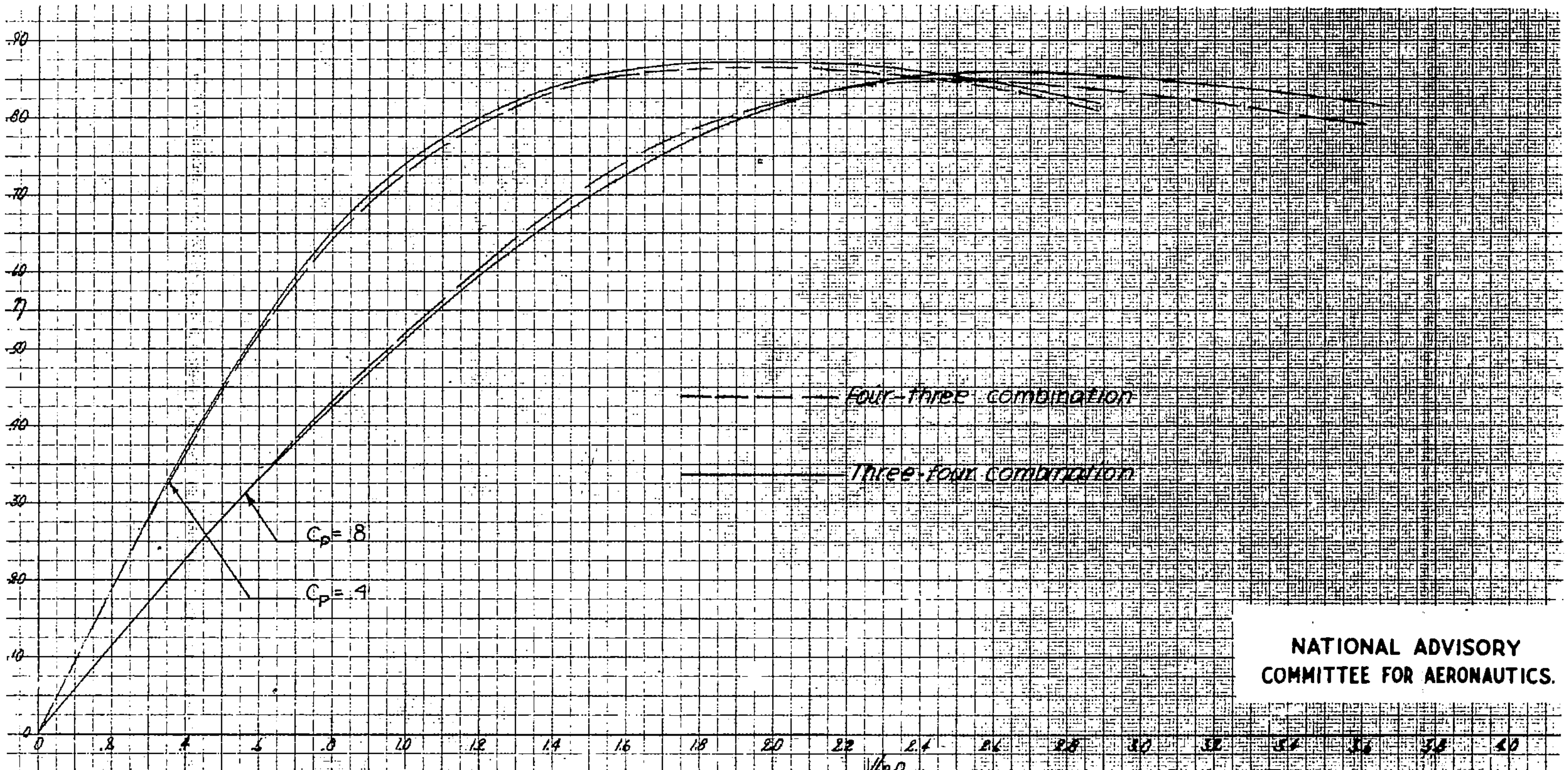

Figure 16 – Comparison of efficiencies at constant power for two different combinations of seven-blade dual-rotating propellers.

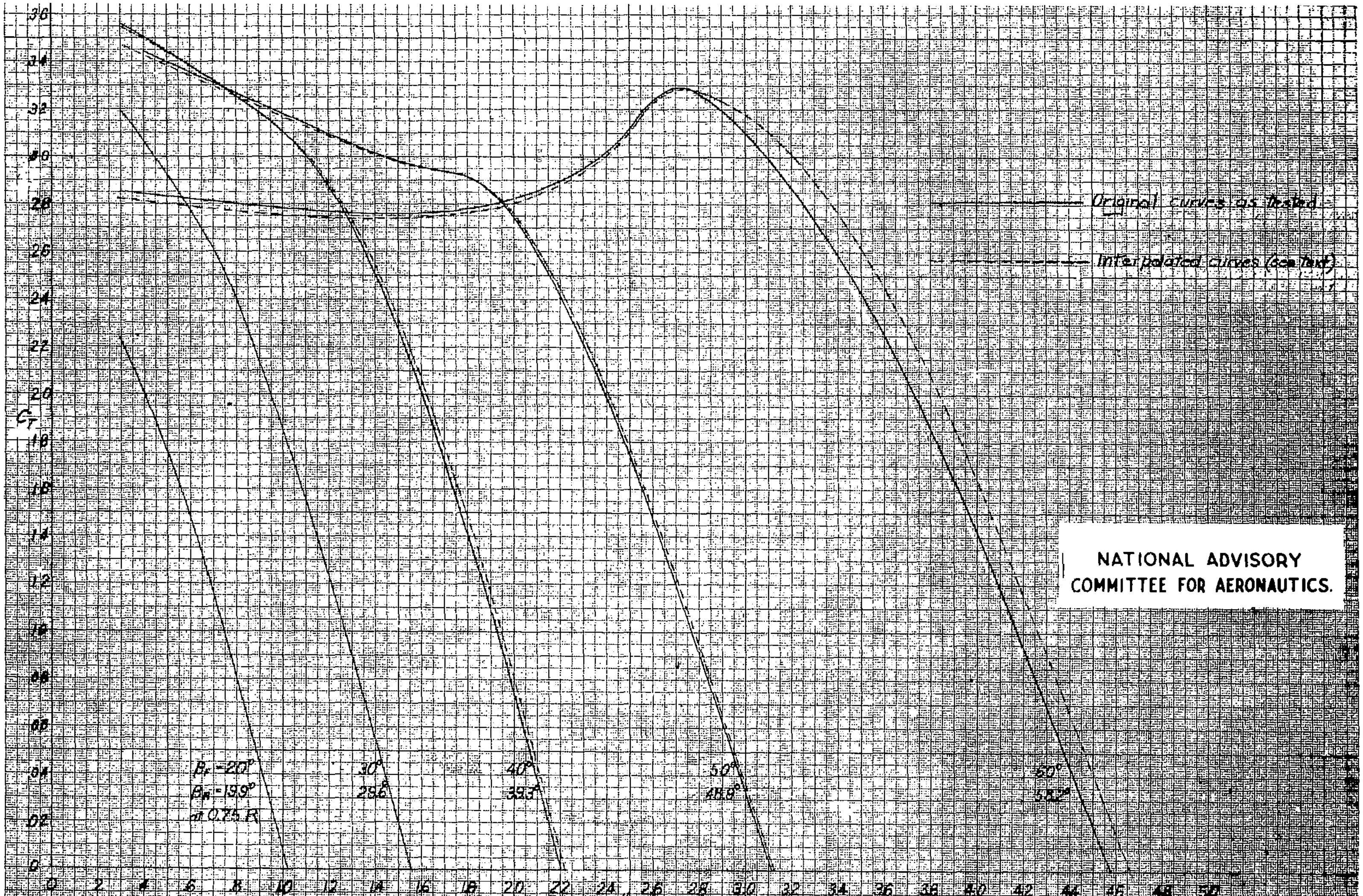

Figure 17.—Thrust-coefficient curves for six-blade dual-rotating propeller operating with speed of rear propeller continuously adjusted to maintain torque equal to the torque of the front propeller.

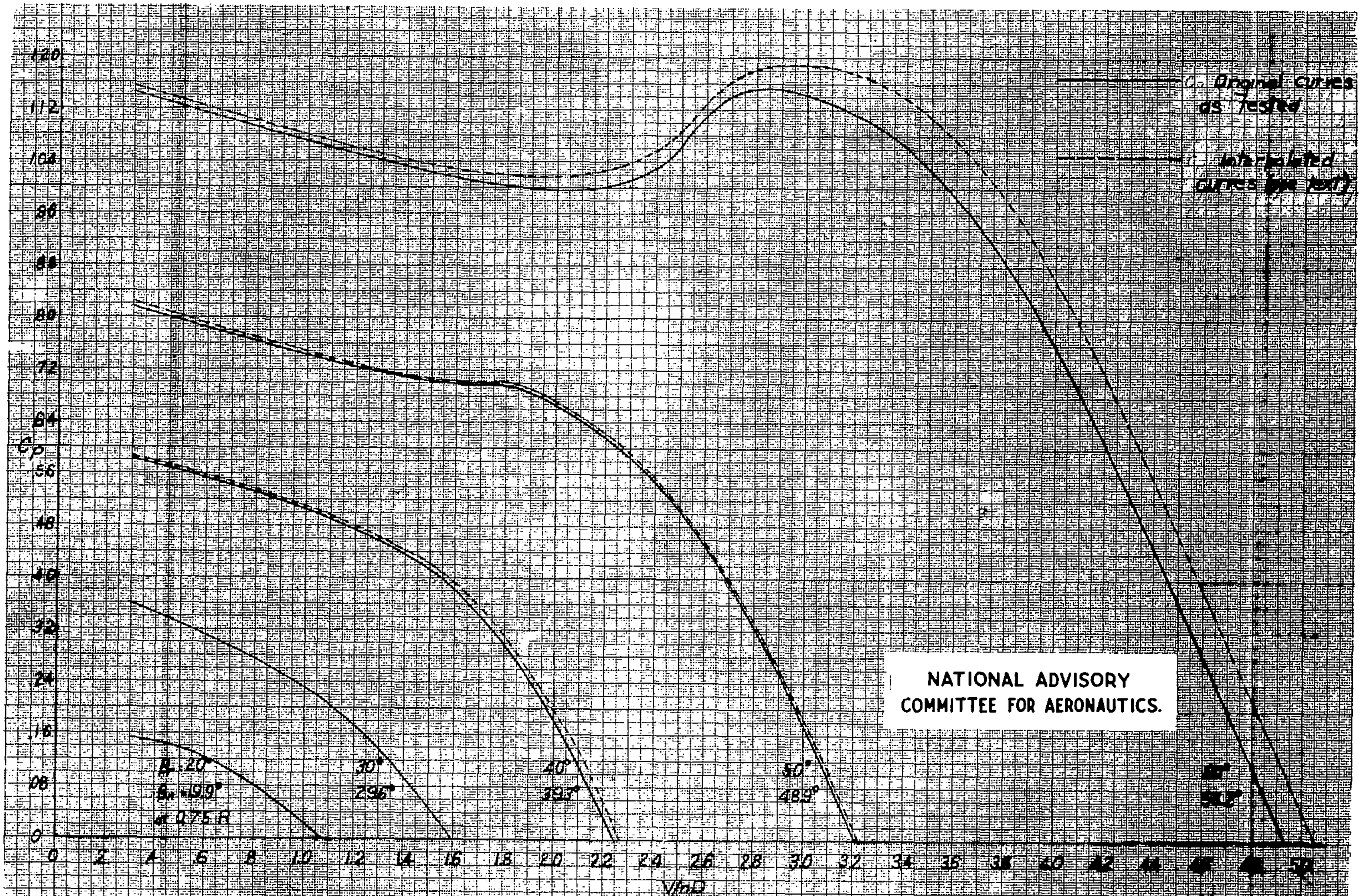

Figure 18.- Power-coefficient curves for six-blade dual-rotating propeller operating with speed of rear propeller continuously adjusted to maintain torque equal to the torque of the front propeller.

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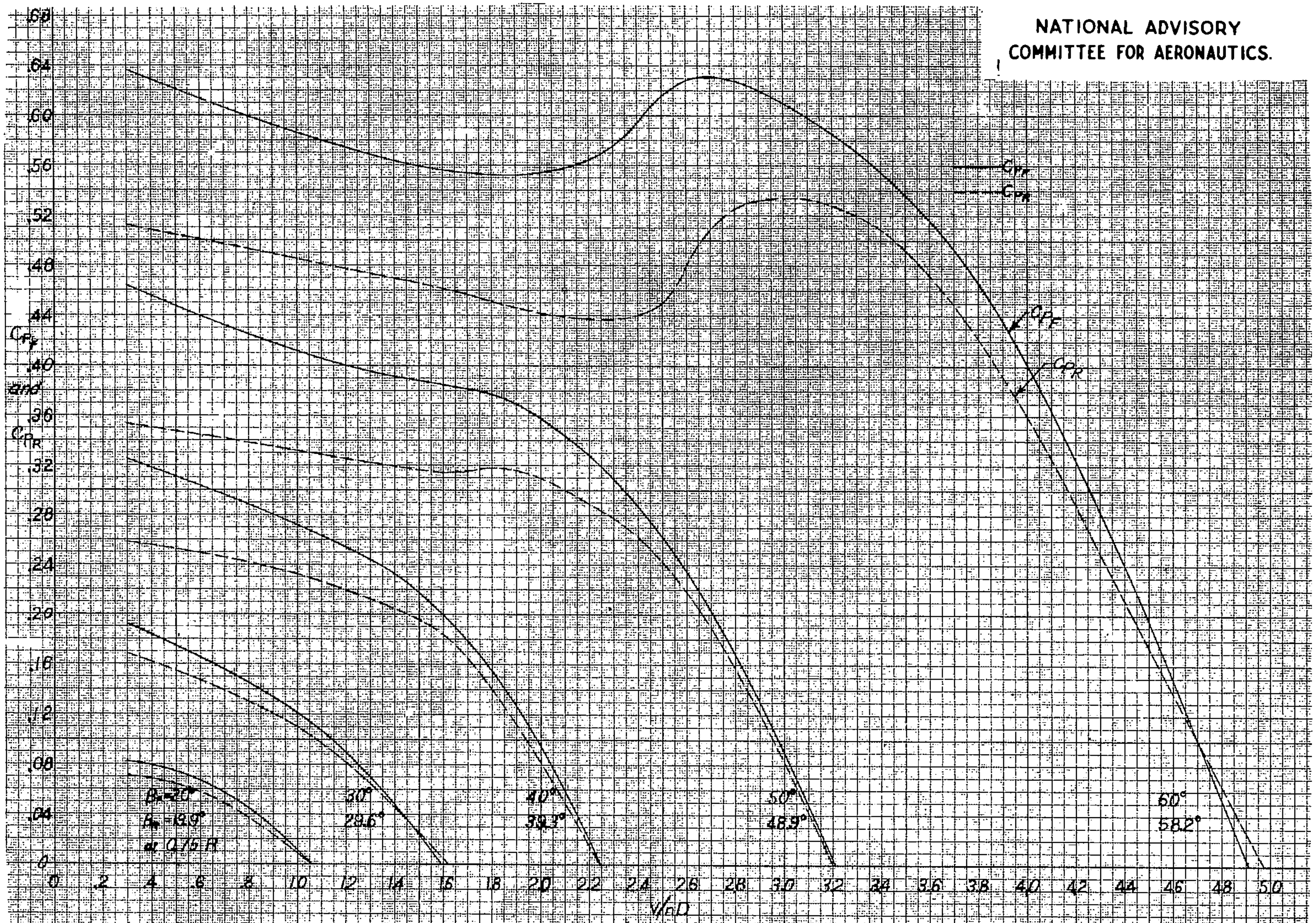

Figure 19.- Individual power-coefficient curves for six-blade dual-rotating propeller operating with speed of rear propeller continuously adjusted to maintain torque equal to the torque of the front propeller.

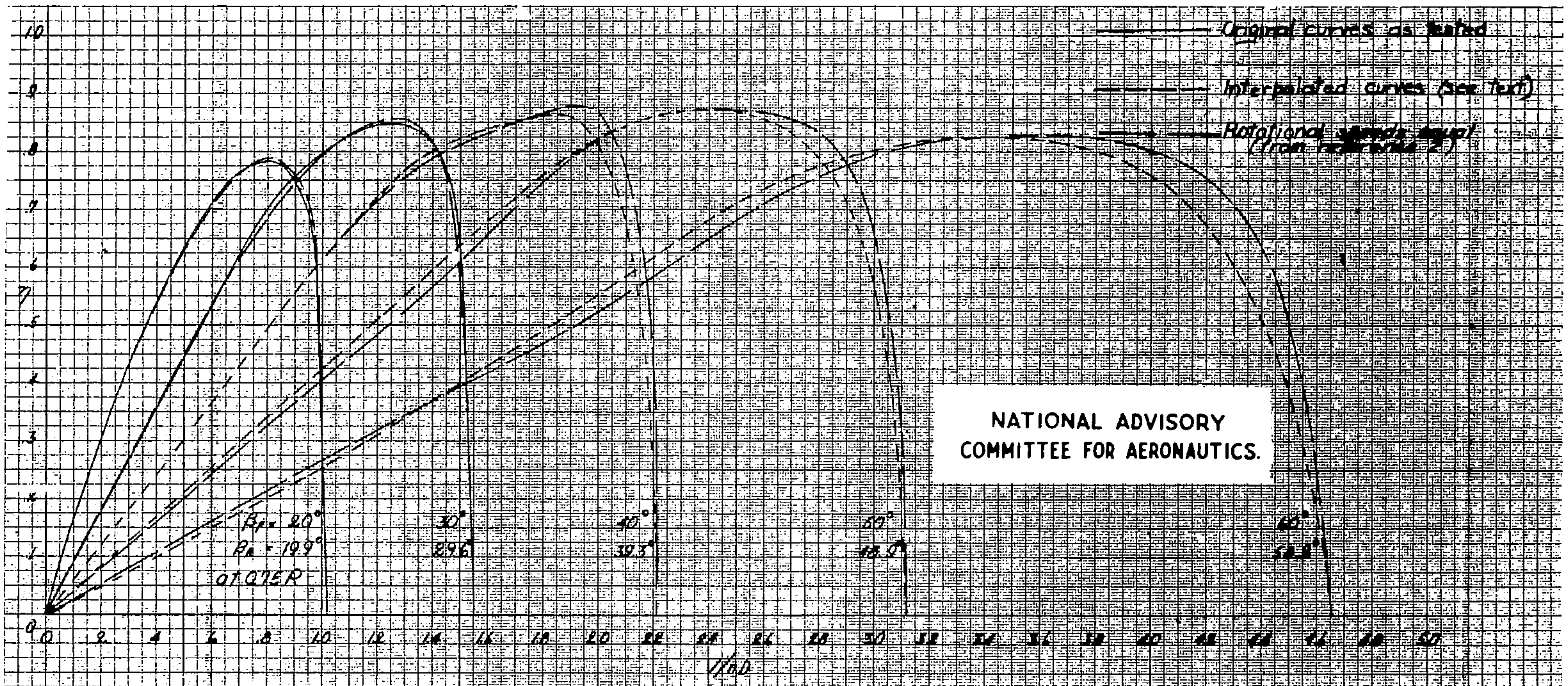

Figure 20.- Superimposed efficiency curves for a six-blade dual-rotating propeller showing difference between operating with speed of rear propeller continuously adjusted to maintain torque equal to the torque of the front propeller and operating at equal speed.

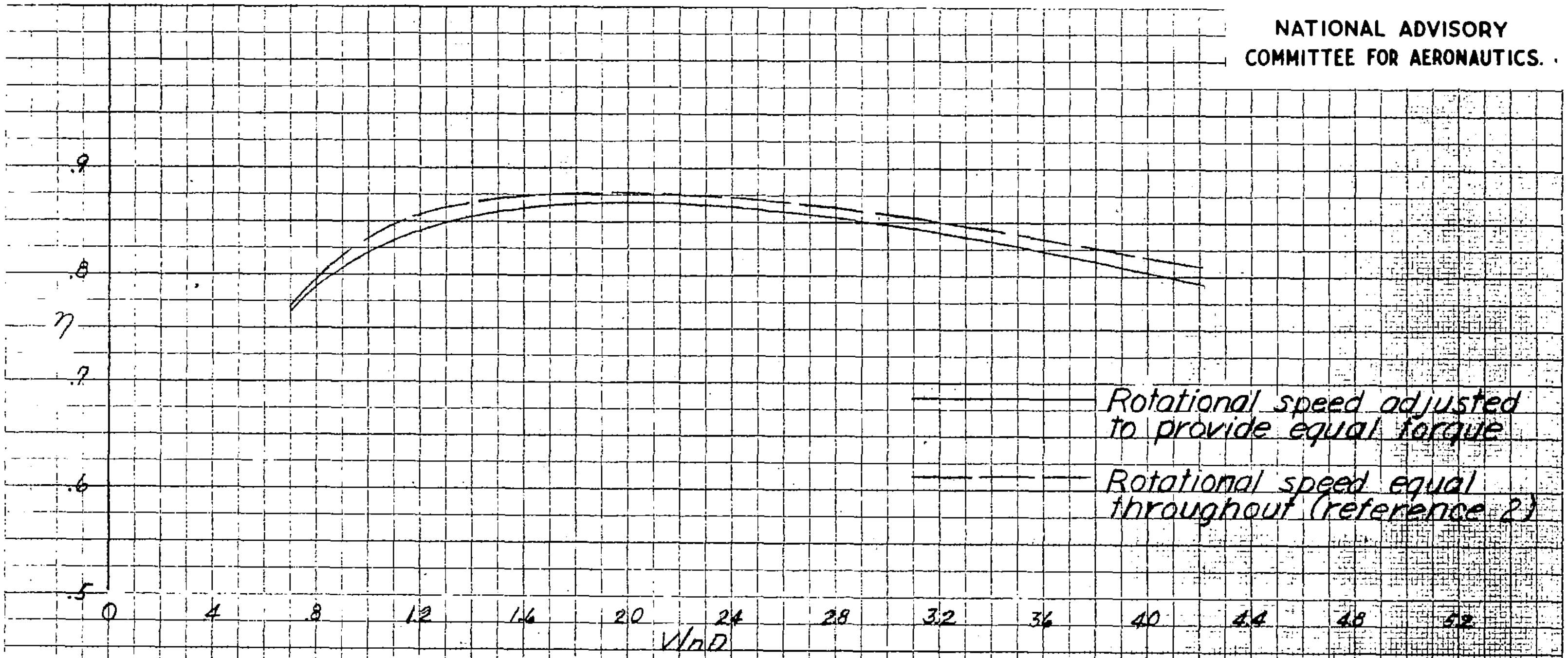

Figure 21.- Efficiency-envelope comparison of the two conditions of equal propeller speed and equal propeller torque. Six-blade dual-rotating propeller.

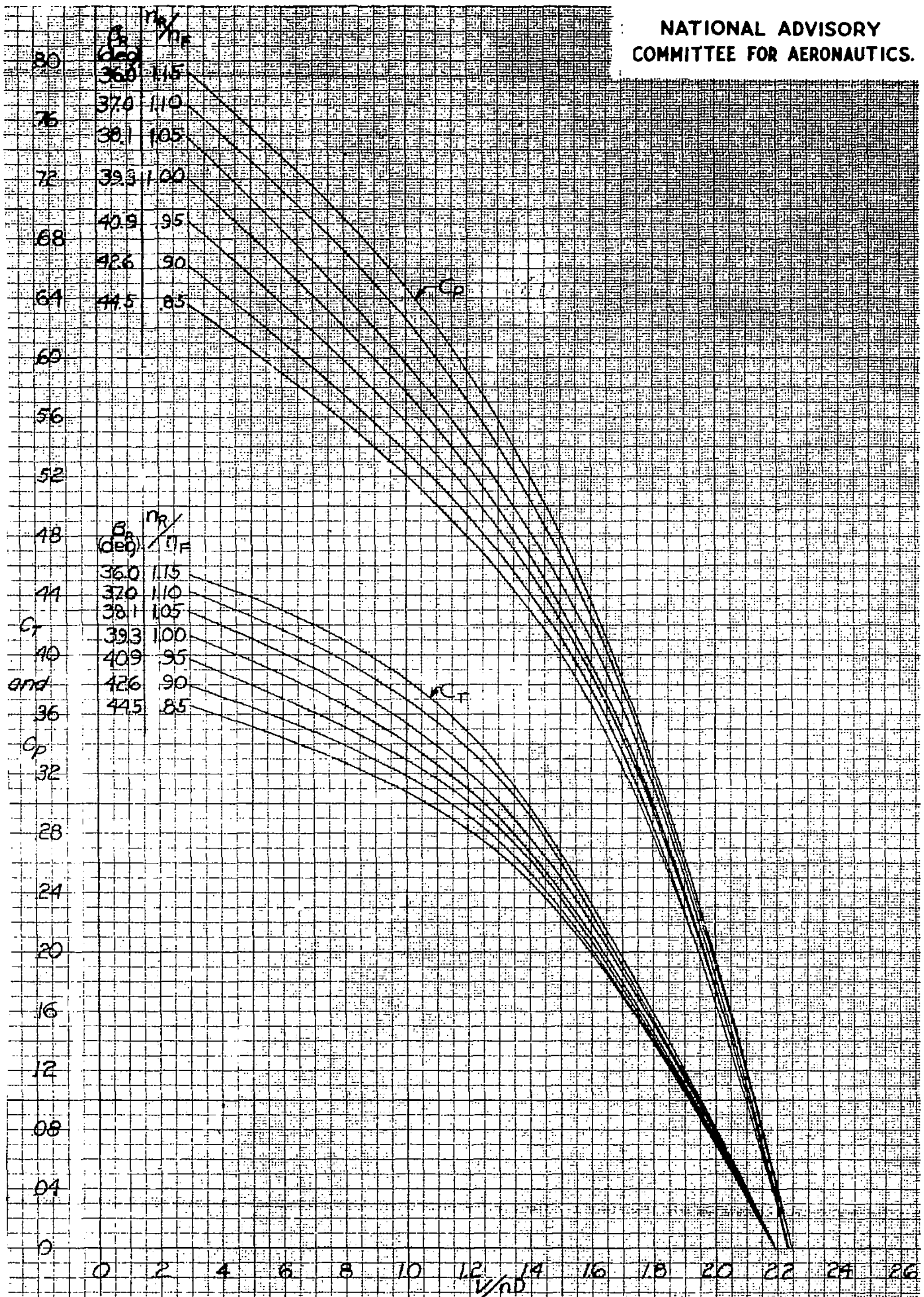

Figure 22.- Propeller curves showing the effect of small variations in speed of the rear propeller of a six-blade dual-rotating combination. Front blade angle was 40°; rear blade angle was adjusted to give equal torque at peak efficiency.

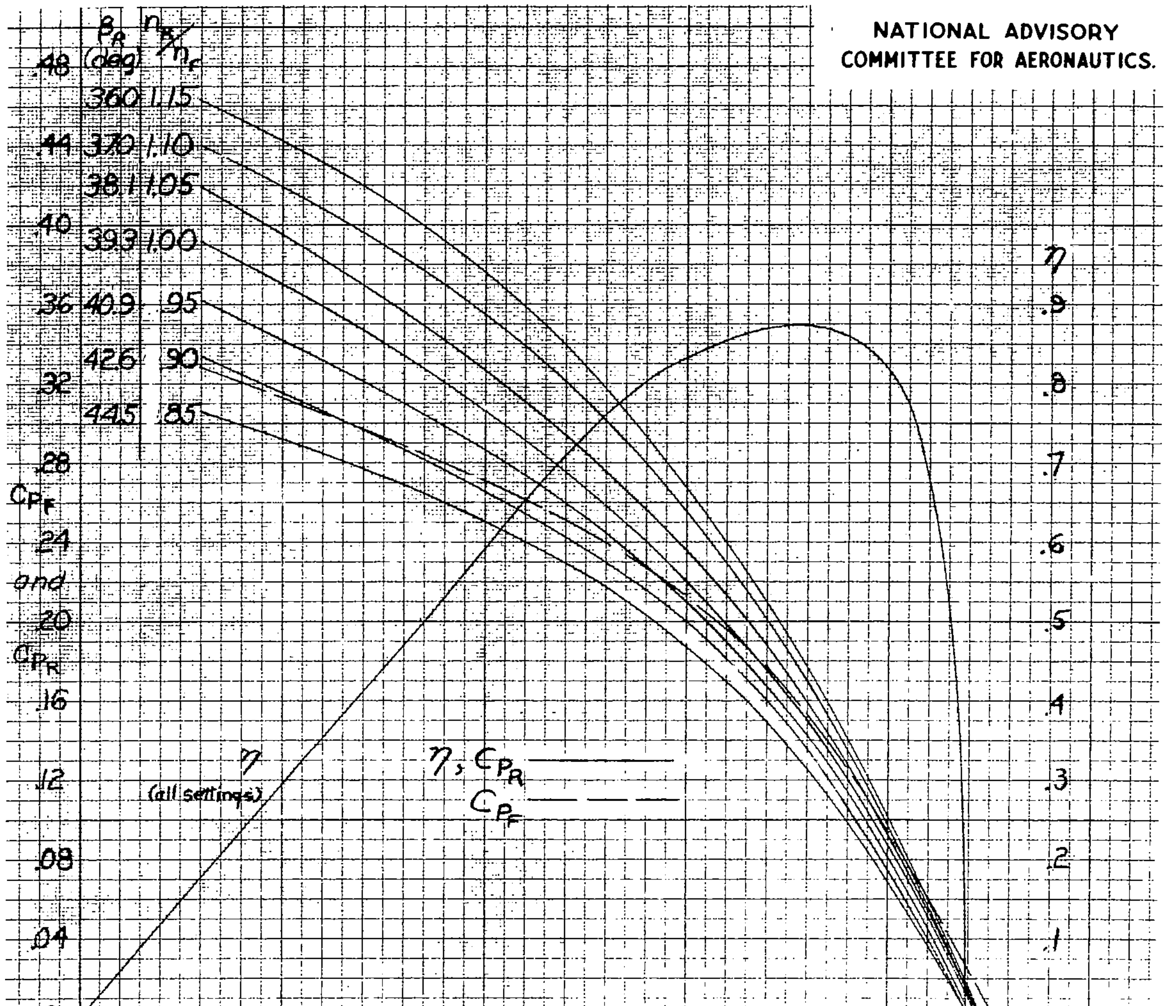

Figure 23.- Propeller curves showing the effect of small variations in speed of the rear propeller of a six-blade dual-rotating combination. Front blade angle was 40°; rear blade angle was set to give equal torque at peak efficiency.

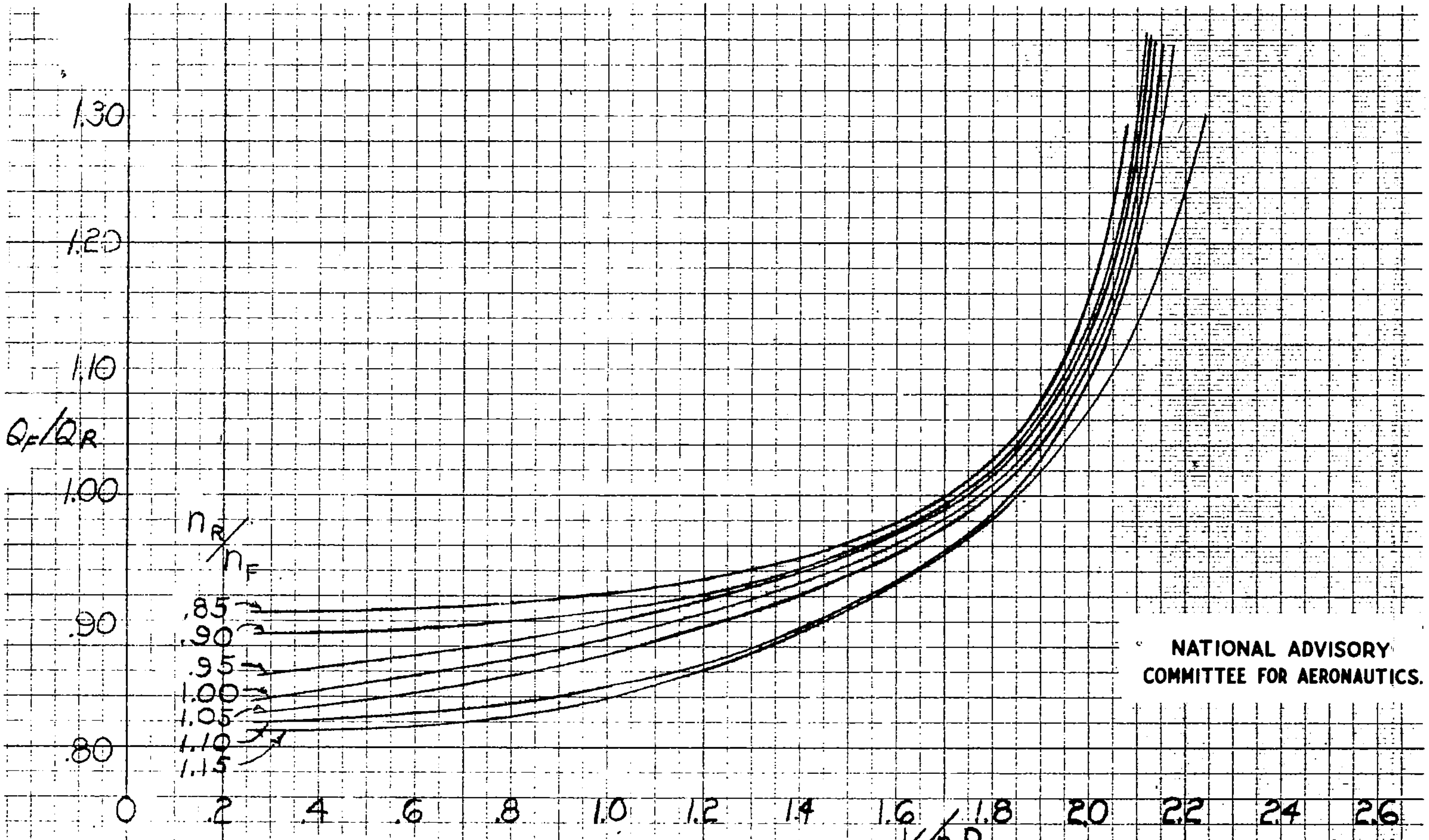

Figure 24.- Effect of small variations in speed of the rear propeller on the ratio of torque for the front and rear propeller. Six-blade dual-rotating propeller; front blade setting, 40°; rear blade angle set to give equal torque at peak efficiency.

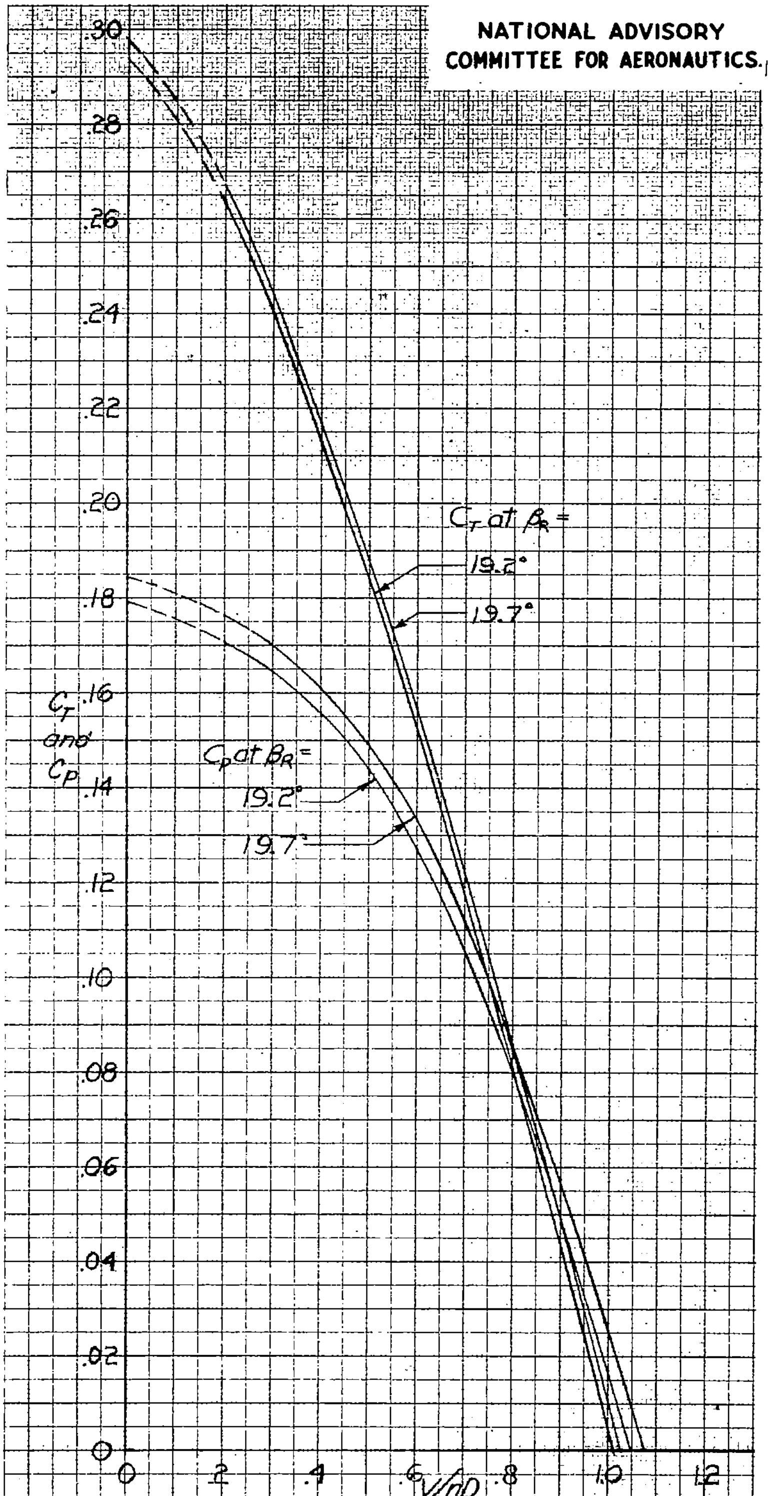

Figure 25.- Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 20° at 0.75R.

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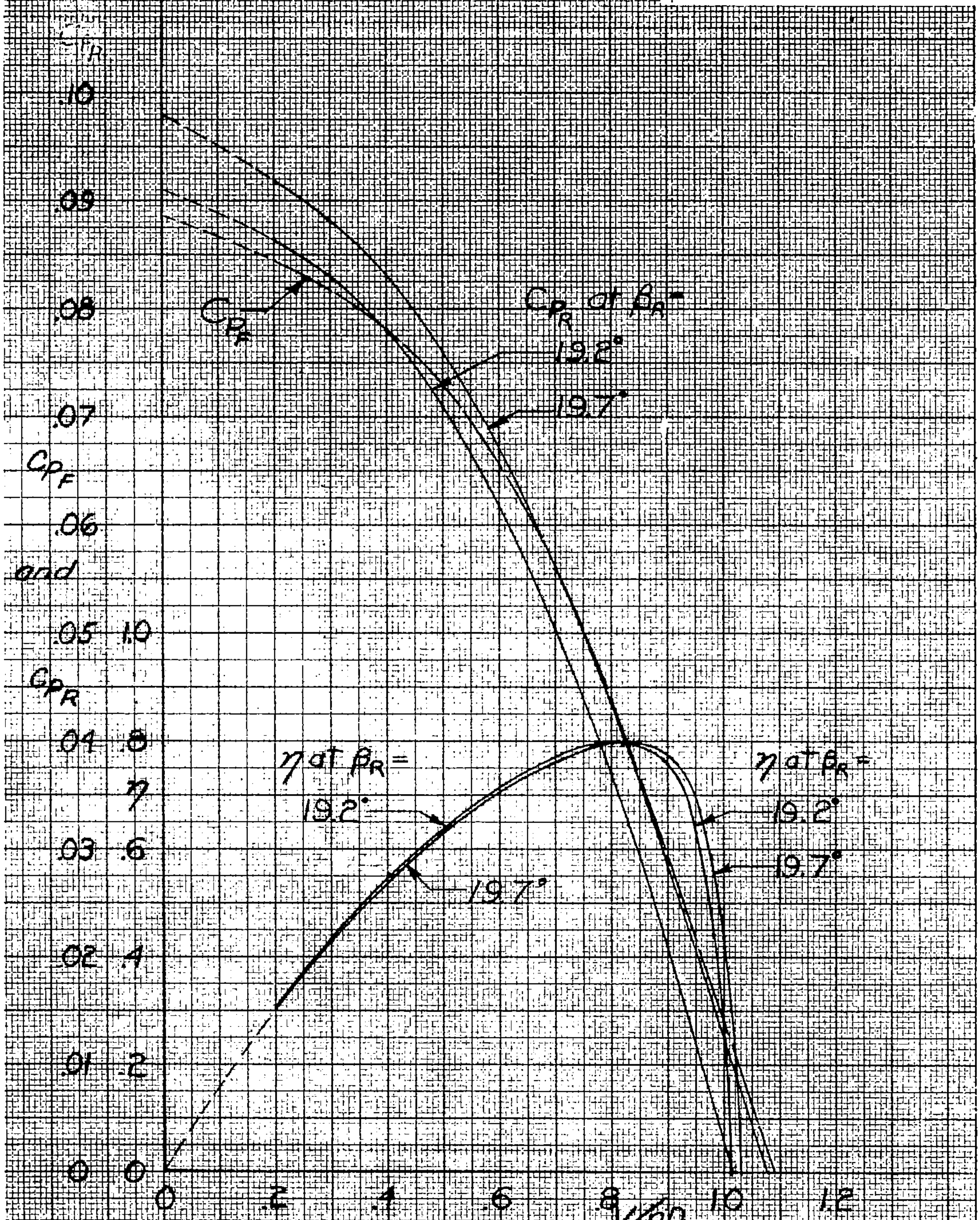


Figure 26.- Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 20° at 0.75R.

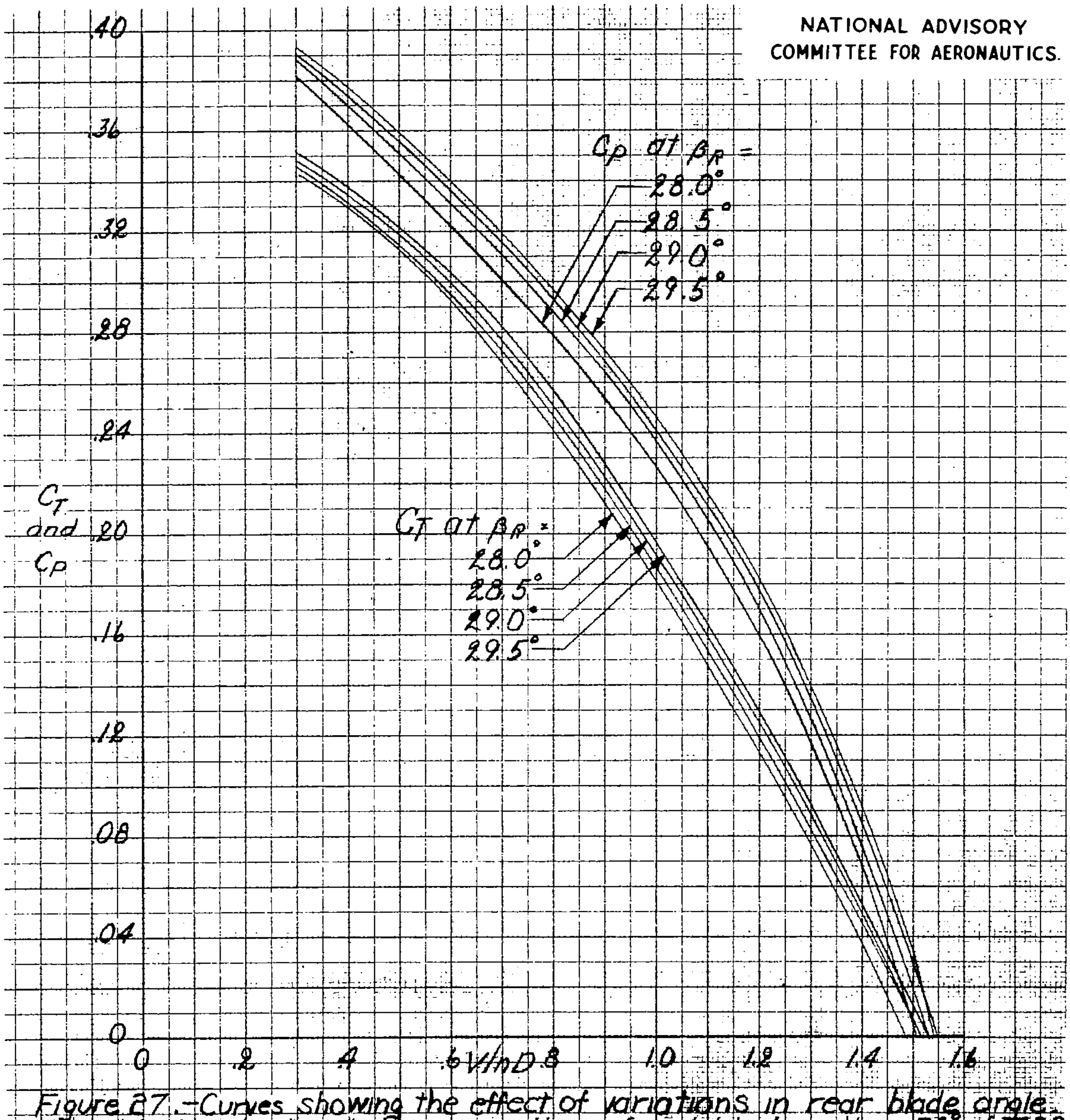


Figure 27.–Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 30° at 0.75R

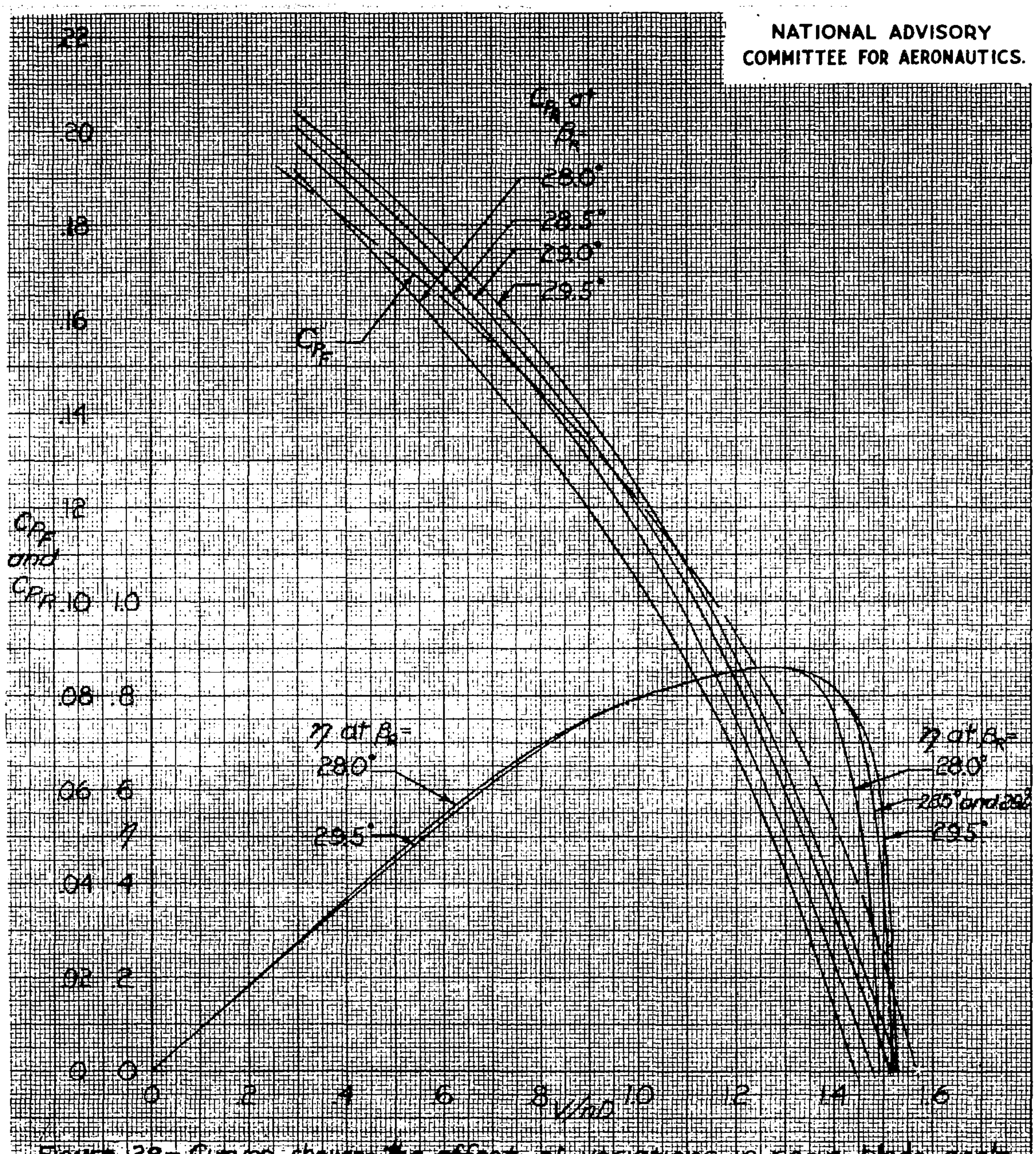


Figure 28.- Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 30° at 0.75R.

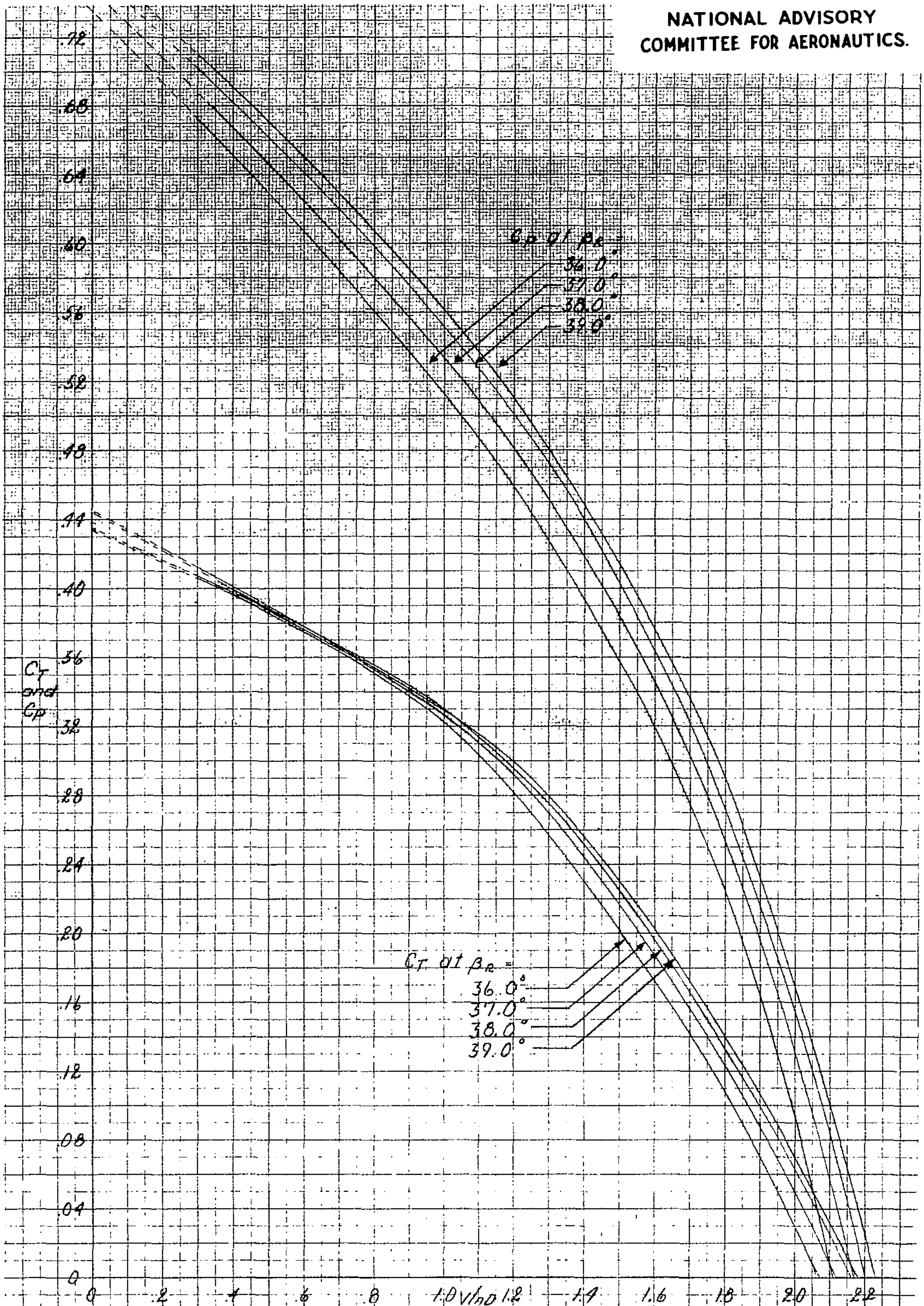


Figure 29.- Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 40° at 0.75R

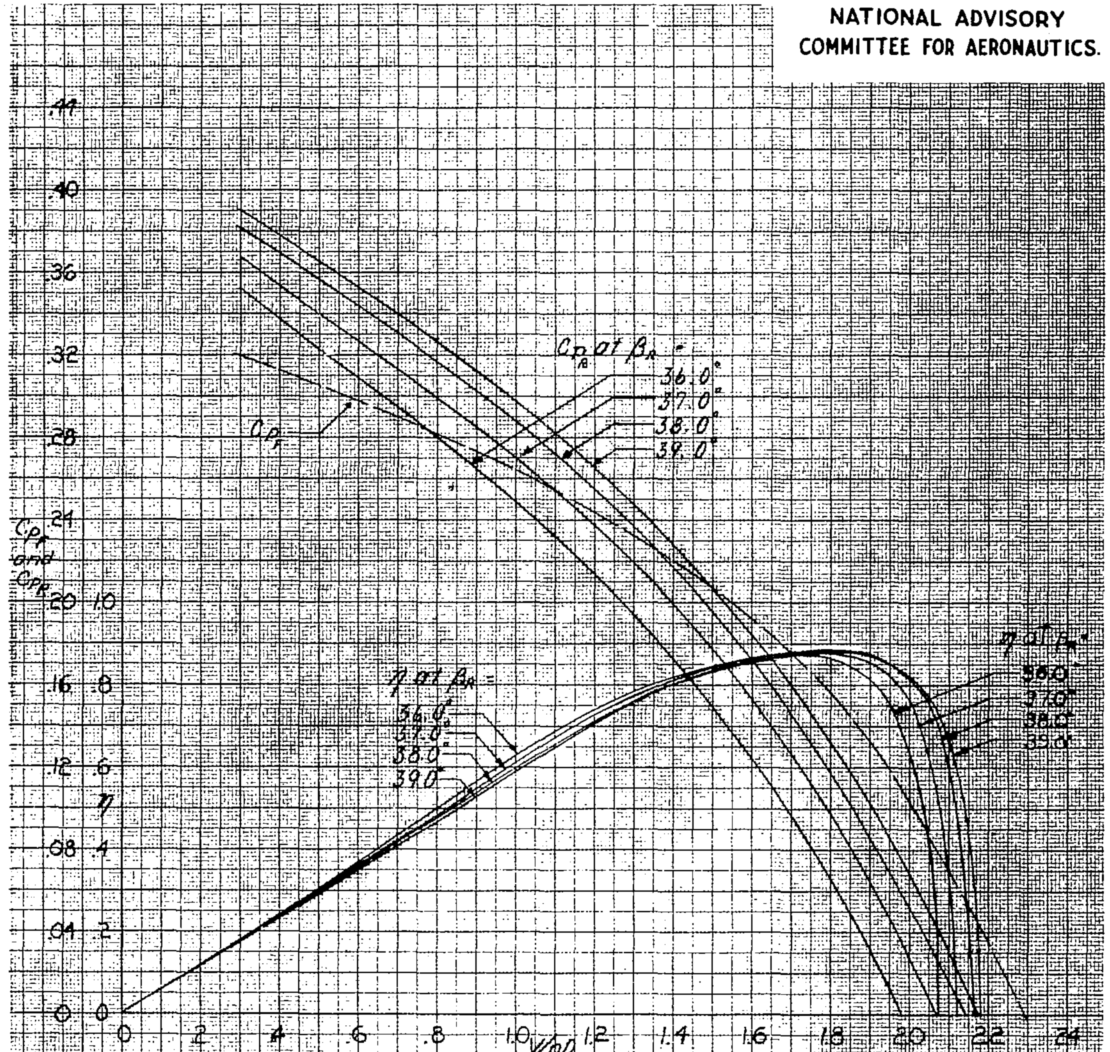


Figure 30 - Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 40° at 0.75R.

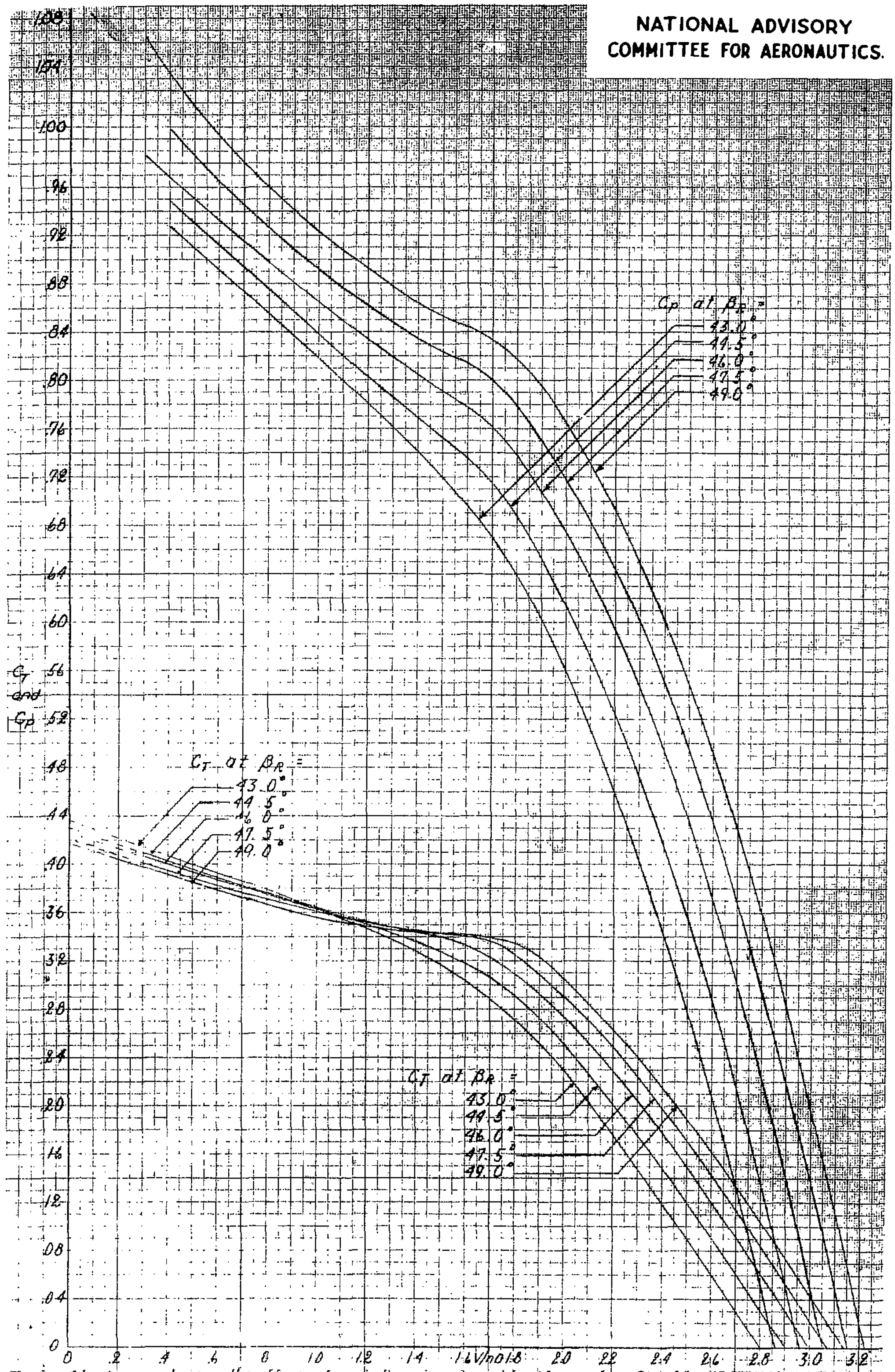


Figure 31.- Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 50° at 0.75 R.

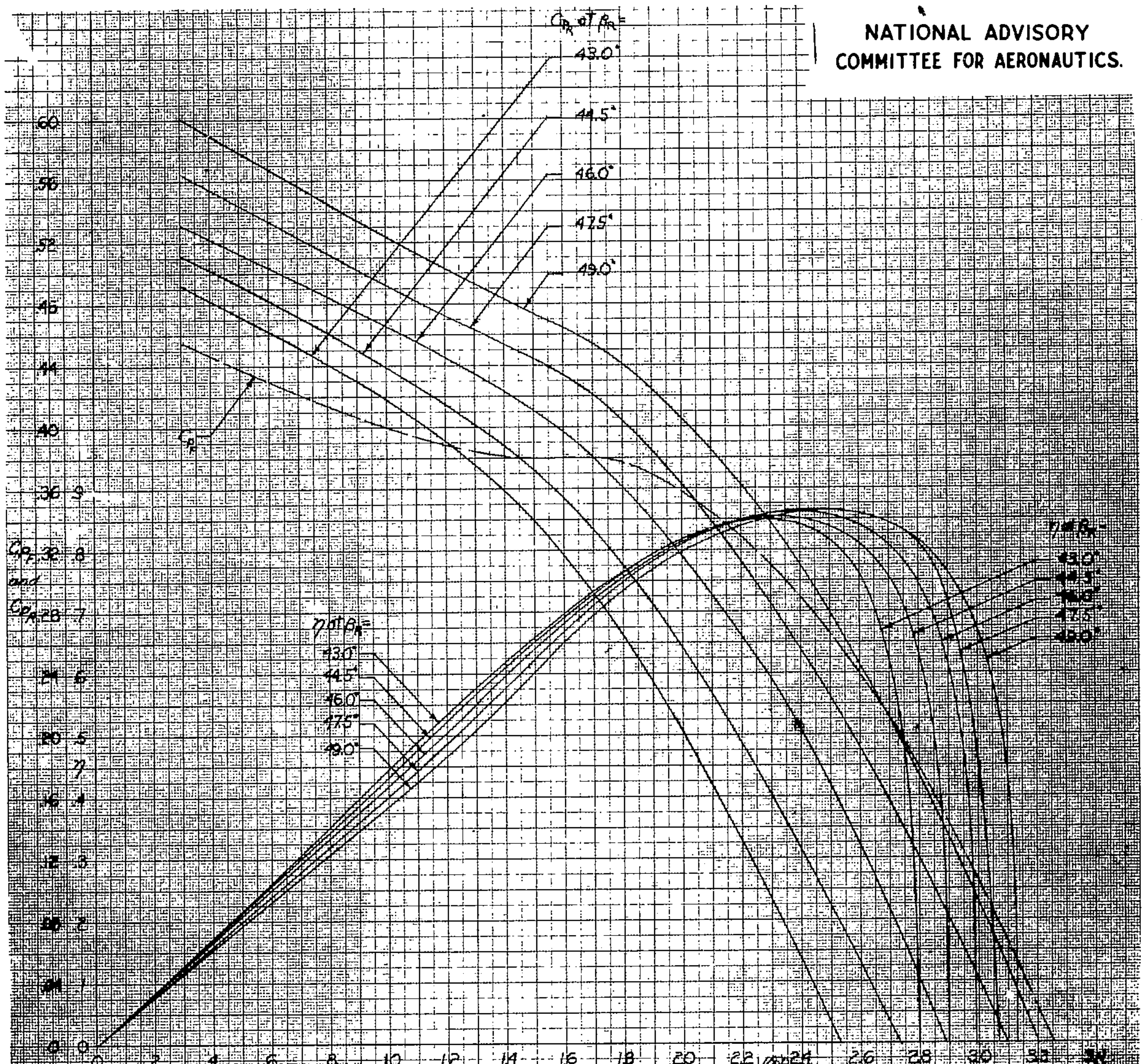


Figure 32.- Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting 50°

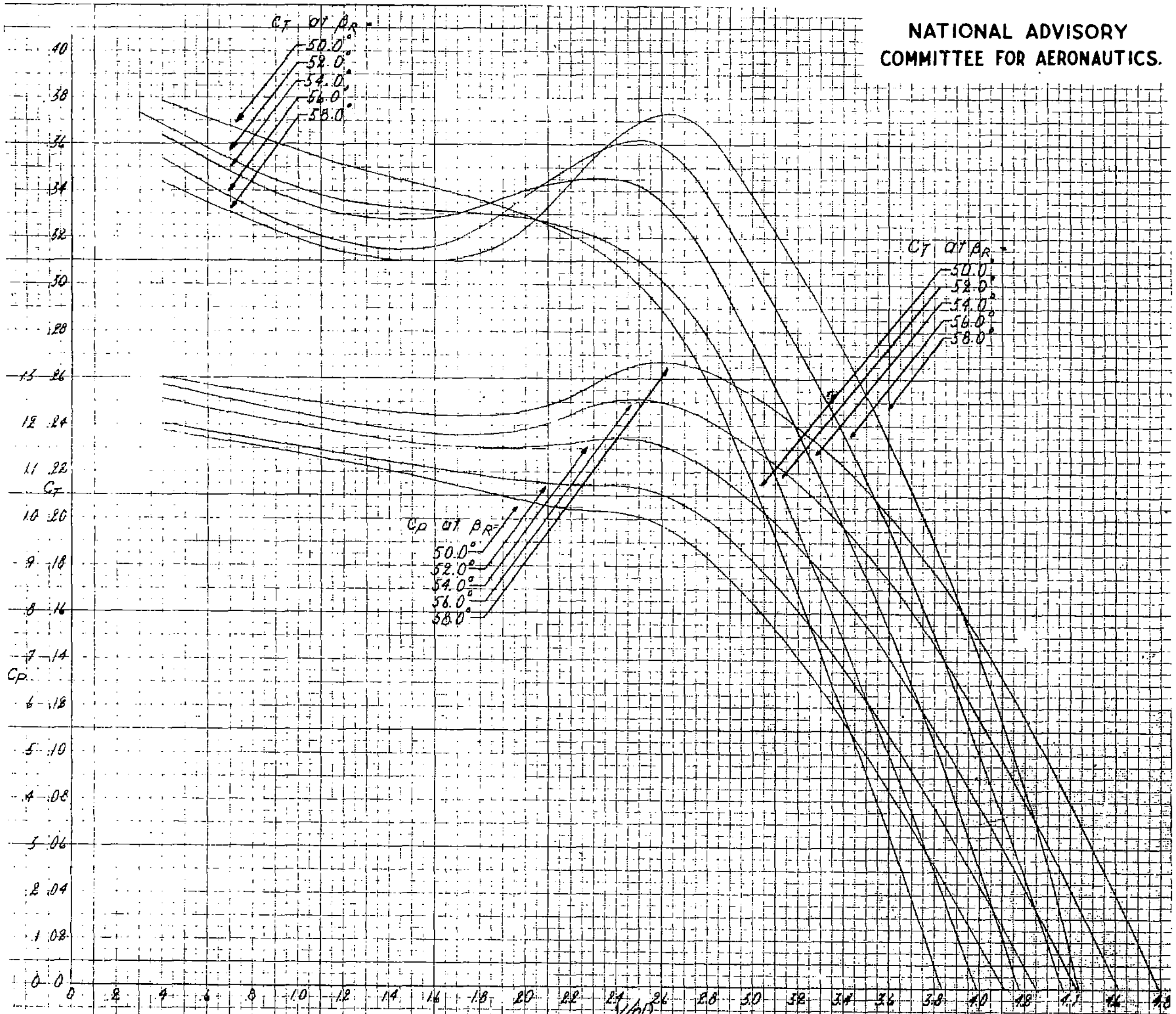
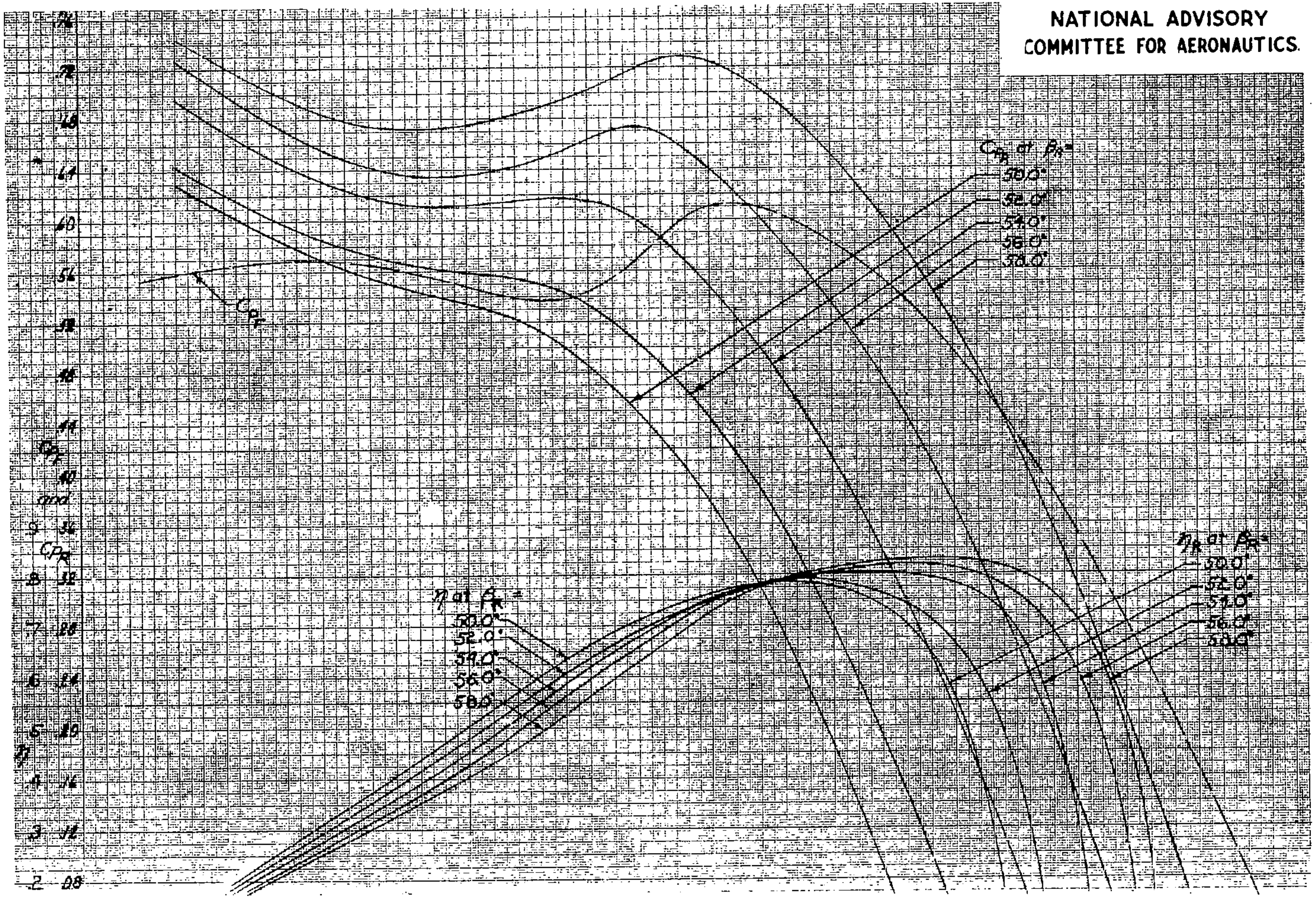


Figure 33. - Curves showing the effect of variations in rear blade angle. Six-blade dual-rotating propeller; front blade setting, 60° at 0.75R.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C_{P_R} at β_R =
50.0°
52.0°
54.0°
56.0°
58.0°
C_{P_F}
η_R at β_R =
50.0°
52.0°
54.0°
56.0°
58.0°
η at β_R =
50.0°
52.0°
54.0°
56.0°
58.0°
C_{P_F} and C_{P_R}
η
.76
.72
.68
.64
.60
.56
.52
.48
.44
.40
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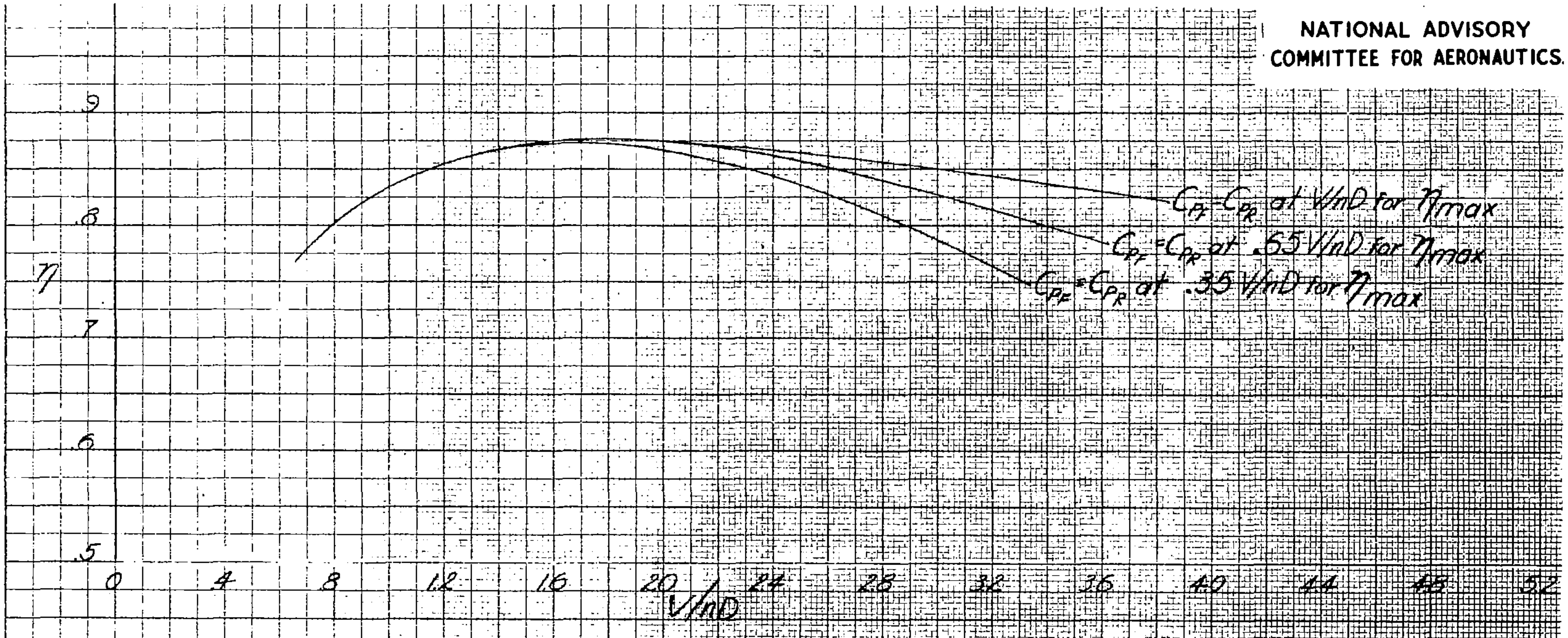

Figure 35.- Effect of change in rear blade angle on the efficiency envelope for three operating conditions. Six-blade dual-rotating propeller.

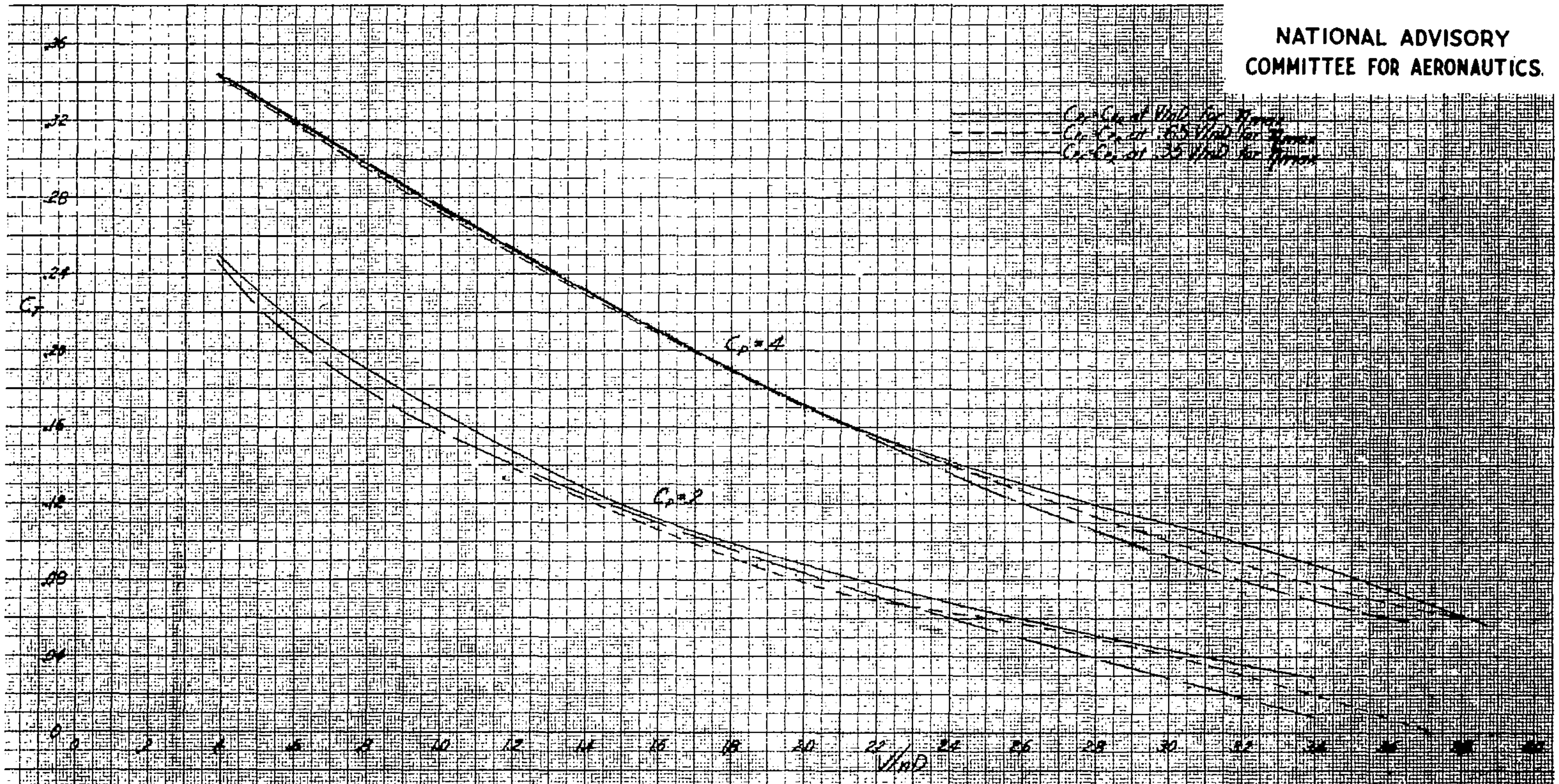

Figure 36.- Thrust-coefficient comparison at constant power coefficient. Six-blade dual-rotating propeller.

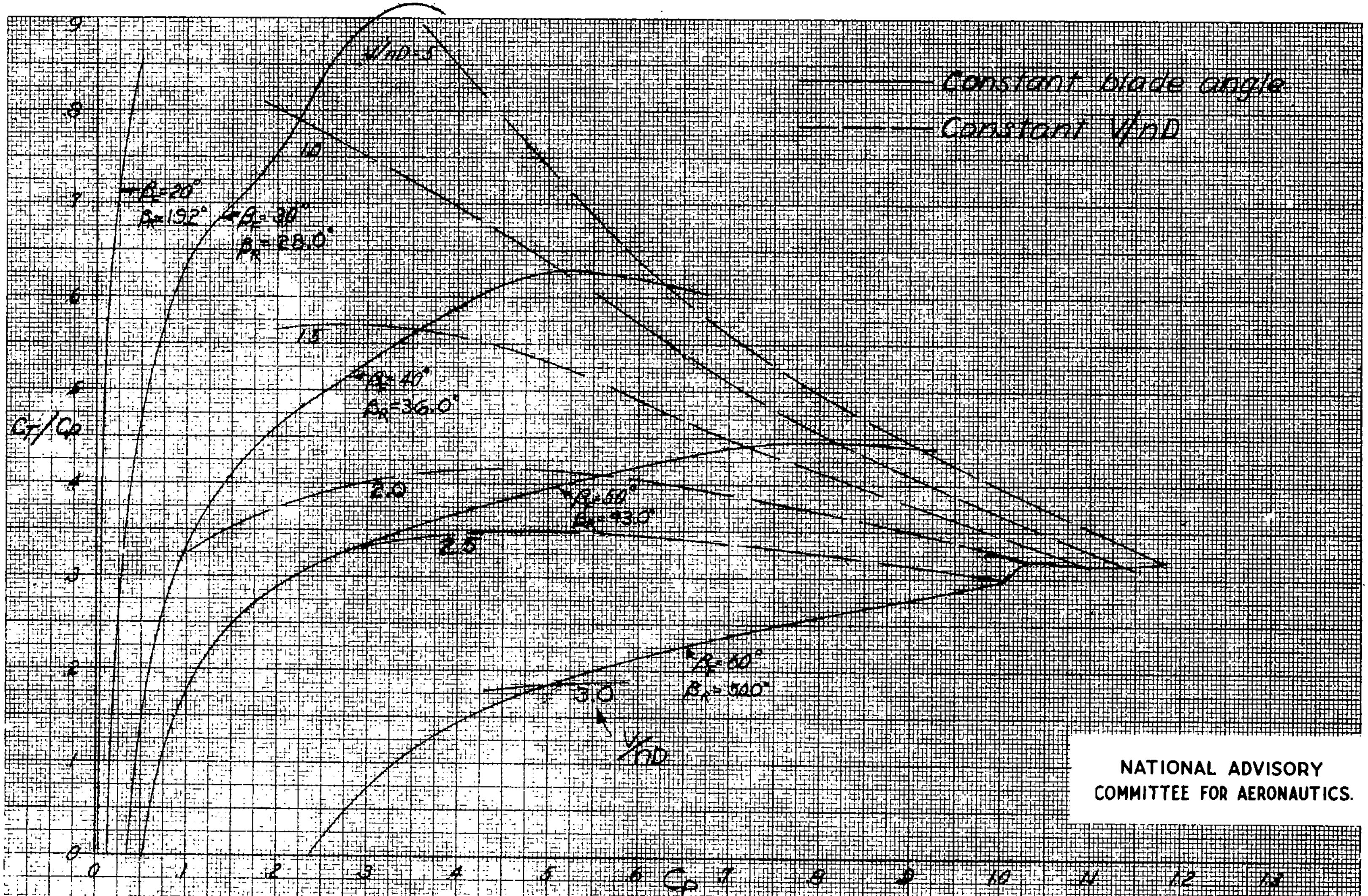

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Figure 37.—Variation of thrust-power ratio with C_P for constant V/nD and constant β_F. Blade angles at 0.75R adjusted to give $C_{P_F}=C_{P_R}$ at approximately 0.35 V/nD for maximum η.

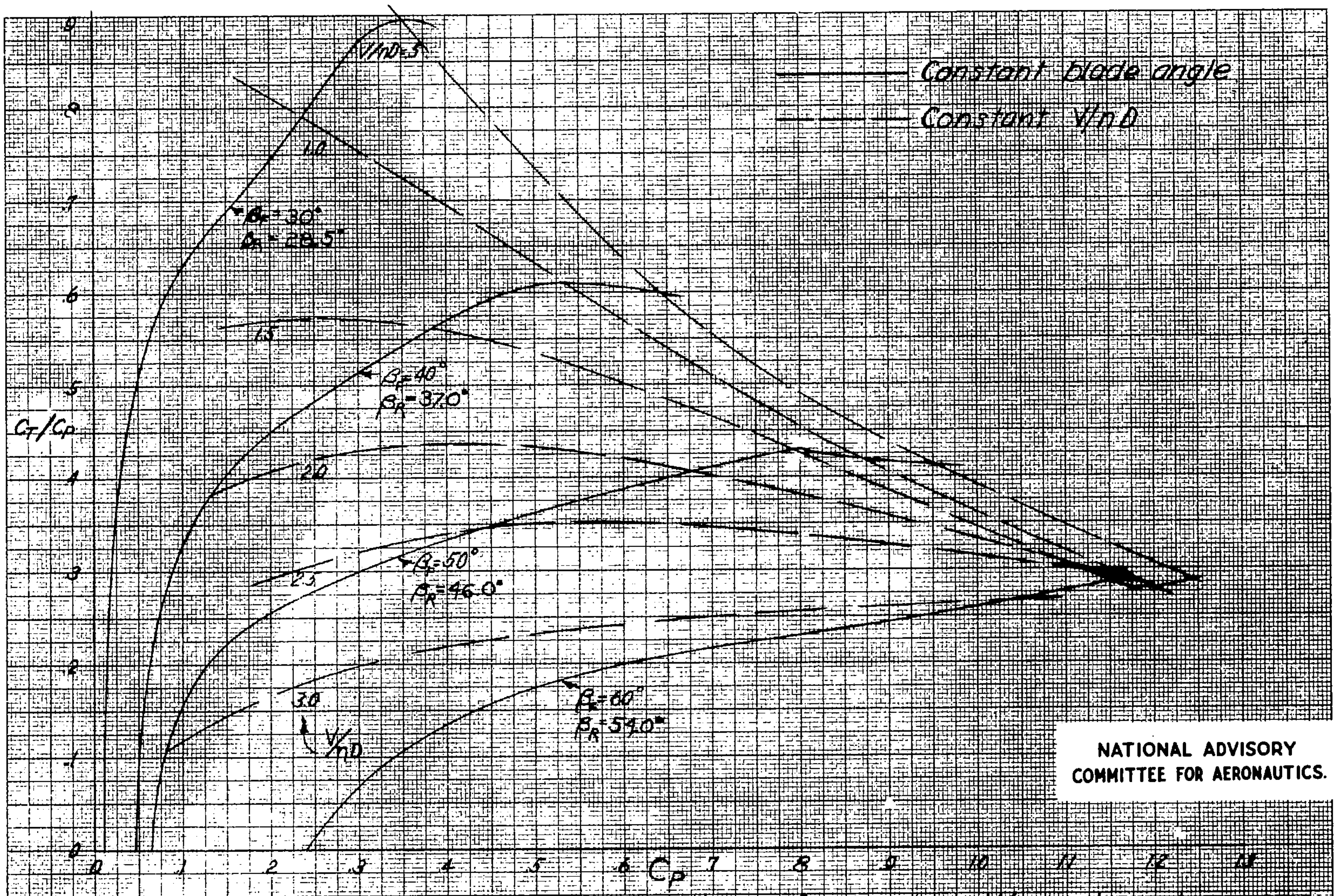

Figure 38 - Variation of thrust-power ratio with C_P for constant V/nD and constant β_F. Blade angles at 0.75R adjusted to give $C_{P_F} = C_{P_R}$ at approximately 1.65 V/nD for maximum η.

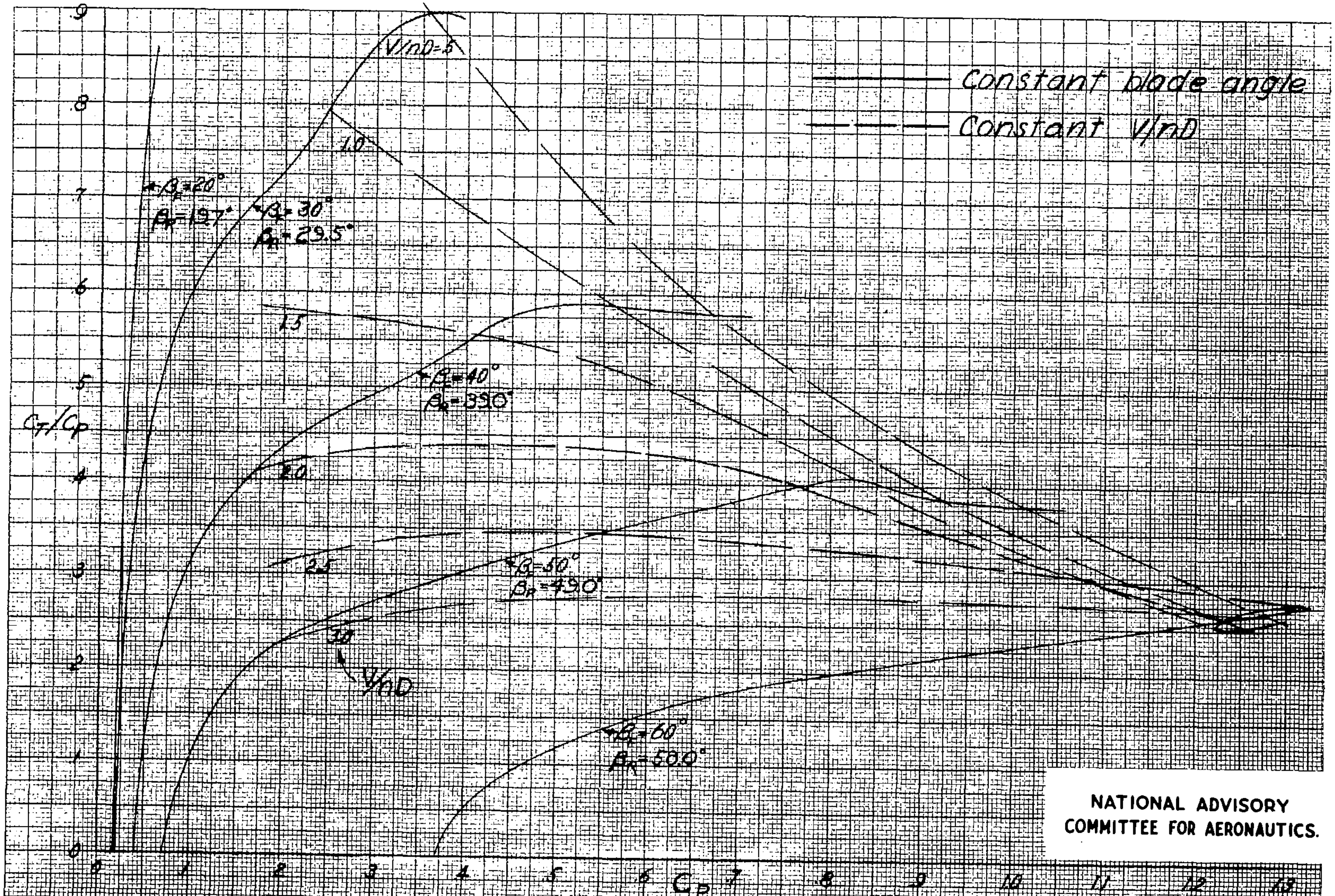

Figure 39.— Variation of thrust-power ratio with C_P for constant V/nD and constant β_F. Blade angles at 0.75R adjusted to give $C_{P_F} = C_{P_R}$ at approximately V/nD for maximum η.

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